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Joshua L. Baker for the degree of Master of Science in Civil Engineering presented on November 22, 2013

Title: Mooring Analysis of the Ocean Sentinel through Field Observation and Numerical Simulation

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Solomon C. Yim

This study presents a mooring analysis of the Ocean Sentinel buoy, which is a mobile test platform for Wave Energy Converters. The Ocean Sentinel is owned and operated by the Northwest National Marine Renewable Energy Center (NNMREC) at Oregon State University (OSU). The study involved a field observation as well as a numerical model. The Ocean Sentinel was deployed from 29 Jul 2013 – 04 Oct 2013 at the NNMREC North Energy Test Site, which is located between 2 – 3 nautical miles (3.7 – 5.6 km) offshore of Yaquina Head, north of Newport, OR. It was configured in a three-point mooring system with load cells on each mooring line. Prior to deployment, the numerical model was used for design and testing of the Ocean Sentinel mooring system. After deployment, recorded environmental conditions were coupled with the model to simulate deployed conditions, and model predictions of tension in the mooring lines were compared with actual results. During the field observation, the Ocean Sentinel experienced a maximum wave height of 39.19 ft (11.94 m) and a maximum mooring line tension of 7999.83 lb (35.58 kN). The numerical model showed mixed correlation with the field data, with statistical force prediction errors of 1.26% – 843.00%. Follow on work to this study will include verification and validation of the numerical model, as well as uncertainty quantification for the model and field data. The Ocean Sentinel mooring system will also be redesigned before the next deployment.

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Mooring Analysis of the Ocean Sentinel through Field Observation and Numerical Simulation

by

Joshua L. Baker

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APPROVED:

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Head of the School of Civil and Construction Engineering

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Dean of the Graduate School

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1 Purpose

The purpose of this study was three-fold. In order of priority, the objectives were:

1. Acquire a dataset of actual loads on the Ocean Sentinel mooring system.
2. Document the deployment and recovery process, and consolidate all pertinent information about the Ocean Sentinel.
3. Create an Ocean Sentinel numerical model, and run preliminary simulations to compare model predictions with field data.

For the 2013 deployment, there were no companies scheduled to test a Wave Energy Converter (WEC). This "lull" in testing was the perfect opportunity to gather new information about the Ocean Sentinel mooring system, and discover possible improvements.

2 Introduction

Mooring systems are used to secure offshore structures to the ocean floor. They can provide general station-keeping, where a ship, buoy, or platform is kept in a general location. They can also provide more finite positioning, where heading, draught, elevation, and GPS coordinates are tightly controlled. The behavior of a mooring system depends greatly on its configuration and components, which is discussed in more detail in this section.

There are two major organizations that produce mooring system specifications: Det Norske Veritas (DNV) and the American Petroleum Institute. DNV specifications are available for free online, and several of them were reviewed during this study (DNV 2005, DNV 2008, and DNV 2010). Additionally, two reports prepared specifically for the Oregon Coast by Sound and Sea Technology Engineering Solutions (SST) were important sources for this study (SST 2009 and SST 2012).

2.1 Mooring Components

There are five main components used in mooring systems: anchors, lines, buoys, connectors, and attachments. Depending on the type of offshore structure, its mooring system may have any number of these components setup in a variety of configurations.

2.1.1 Anchors

There are four main types of anchors used in mooring systems: gravity (deadweight), drag, piles, and plates. A generic version of each anchor type is shown in Figure 1, and each one has a number of specialized designs.

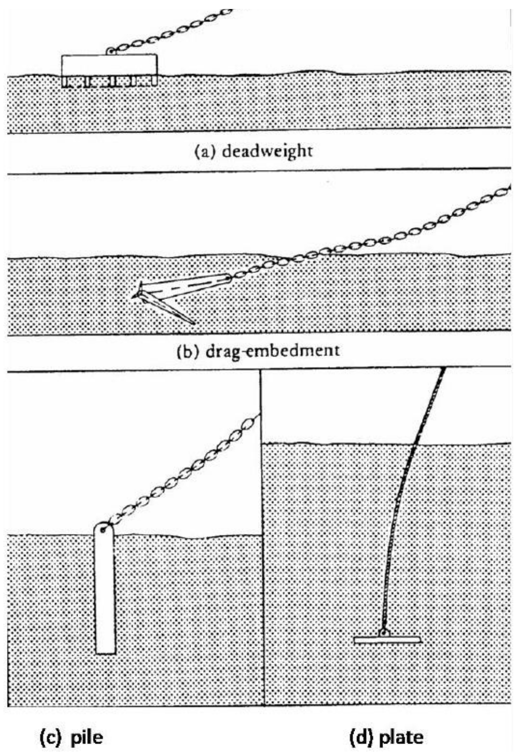

Figure 1: Anchor types (SST 2009)

Gravity anchors typically provide simple solutions that are cheap and easy to design. They work in virtually all soil types, and are sometimes the only option for hard seabeds. However they are inefficient, so they may not be the best solution for large offshore structures or those experiencing large forces. Gravity anchors also become difficult to deploy as they increase in size.

Drag anchors can provide high load capacities, and are much more efficient than gravity anchors. They are easily recoverable, and are often used for boats, ships, and large offshore structures. However, drag anchors have a number of drawbacks, including: they do not work in all soil types, they must be set properly, and they can only resist horizontal loads. Depending on the mooring configuration, they can also greatly increase the underwater footprint.

Piles have the highest load capacity of the four anchor types, and are generally used for large offshore structures. They can resist loads in all directions, and work in a variety of soil types. Piles must be installed into the seabed, and there are three general methods: driving, drilling, or pumping for suction piles. Suction piles are hollow, sealed tubes that are embedded into the seafloor by pumping the water out of them, which creates a pressure differential with the seabed. Pile installation is usually expensive because it requires specialized equipment. Piles are also considered permanent structures (except for suction piles), which can significantly increase environmental concerns and permitting requirements.

Plate anchors are efficient and have a high load capacity. They work in a variety of soil types, and provide a good option in between drag anchors and piles. There are various ways to install plate anchors, including: driving, vibration, jetting, auguring, shooting, or dragging. Plate anchors have a very small profile protruding from the seabed, making them more trawl-friendly than gravity anchors or piles. Plate anchors are generally considered non-recoverable, which presents the same environmental and permitting concerns as piles.

Table 1: Anchor type characteristics and evaluation criteria (SST 2009)

Seafloor Material	Deadweight	Pile	Plate	Drag
Soft clay, mud	++	+	++	++
Soft clay layer (0-20 ft) over hard layer	++	++	o	+
Stiff clay	++	++	++	++
Sand	++	++	++	++
Hard glacial till	++	++	++	+
Boulders	++	o	o	o
Soft rock or coral	++	++	++	+
Hard, massive rock	++	+	+	o
Seafloor Topography				
Slope < 10 deg	++	++	++	++
Slope > 10 deg	o	++	++	o
Loading Direction				
Omnidirectional	++	++	++	o
Unidirectional	++	++	++	++
Large uplift	++	++	++	o
Lateral Load Range				
To 100,000 lb	++	+	++	++
100,000 to 1,000,000 lb	+	++	+	++
Over 1,000,000 lb	o	++	o	o

++ Functions well
+ Functions, but not normally the best choice
o Does not function well

2.1.2 Lines

There are three basic line types used in mooring systems: steel chain, steel wire rope, and synthetic rope. Each type of line has different characteristics that provide benefits for different applications. Steel chain is durable, cost-effective, and abrasion resistant. It is also easy to inspect and repair. However, steel chain is heavy and negatively buoyant, so a very long chain can outweigh the buoyancy of the structure it is supporting, making it ineffective for deep-water applications. It is also awkward to handle, which can make deployment difficult. Steel chain is available in two types, stud and stud-less, which are shown in Figure 2 and Figure 3, respectively. Steel chain is best suited for shallow catenaries that will contact the seabed, or in short lengths near anchors.

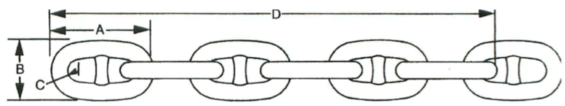

Figure 2: US Navy stud-link welded chain specifications (USN 1990)

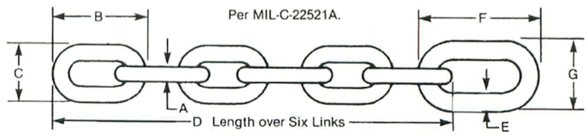

Figure 3: US Coast Guard buoy chain specifications (SST 2012)

Steel wire rope is available in a variety of designs, which allows it to be easily tailored for specific applications. It is abrasion and corrosion resistant, and generally easier to deploy than chain. Wire rope is usually only designed to withstand tension loads, even though it is stiffer than chain. It can also be torque-balanced, which minimizes spin when handling mooring anchors. Wire rope is generally defined by the number of strands in the rope, the number of wires in each strand, and the direction of lay (see Figure 4). It can be used both at the sea surface and on the seabed.

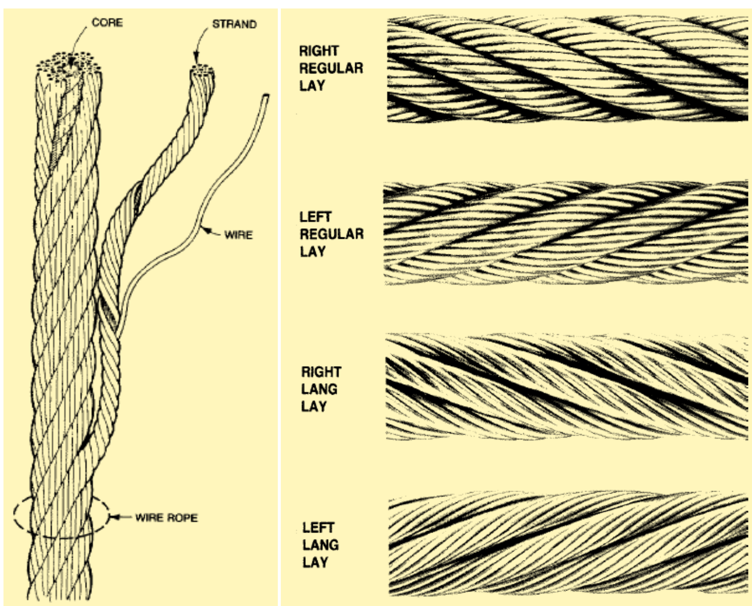

Figure 4: Wire rope construction and lay (WW 2010)

Synthetic rope is usually the most expensive mooring line option. It has a high strength-to-weight ratio and can be neutrally buoyant, making it ideal for deep water moorings. It is easy to store, handle, and deploy. It is also corrosion resistant, and can be easily spliced and terminated. However, synthetic rope has poor abrasion resistance and is susceptible to UV rays. This limits applications to below the sea surface and above the seabed. It should also not be used in situations where line contact and/or rubbing are expected. Synthetic rope can be made from a variety of materials, including nylon, polyester, polypropylene, Kevlar, and HMPE (High Modulus Polyethylene). Typical synthetic rope construction is shown in Figure 5.

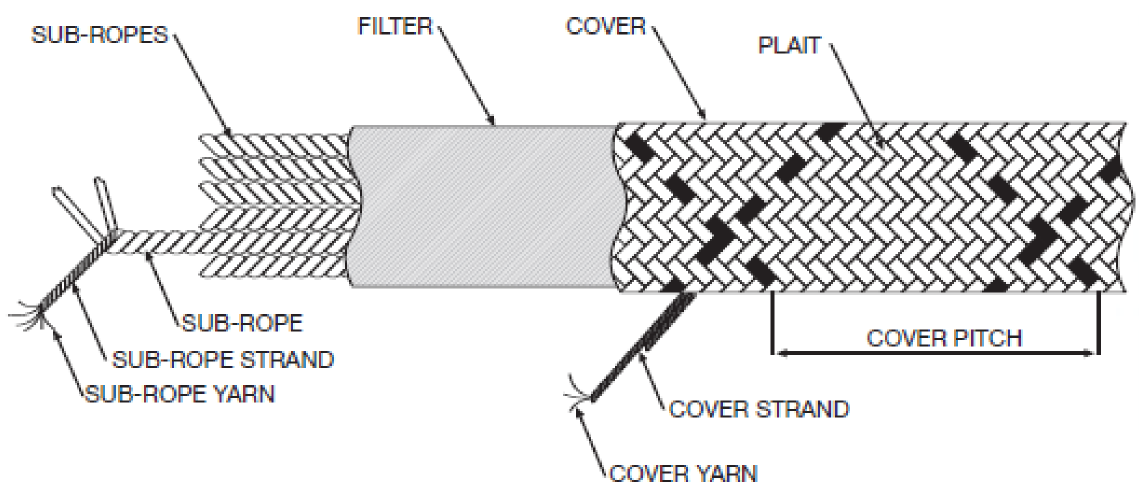

Figure 5: Synthetic rope construction schematic (Bridon 2006)

2.1.3 Buoys

Buoys are generally used in mooring systems to: add compliance, provide buoyancy in specific areas, as markers for anchors or connection points, or aid in deployment/recovery operations. Mooring system buoys are classified as surface or sub-surface, and are generally foam-filled or of hollow steel construction, respectively. Foam-filled buoys are usually more expensive, but are widely used for surface floats because they require little maintenance. They are not usually used for subsurface applications because they are depth-limited. Figure 6 shows a typical foam-filled buoy, and Figure 7 shows spherical steel buoys, similar to what is used in the Ocean Sentinel mooring system.

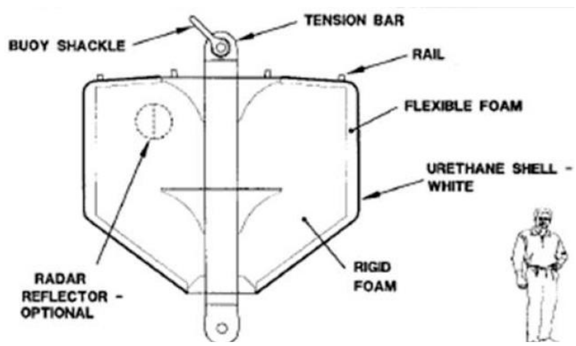

Figure 6: USN Fleet Mooring Buoy (SST 2009)

Figure 7: Example of hollow steel buoy (SST 2012)

2.1.4 Connectors

There are various types of connectors used in mooring systems, including: shackles, swivels, rings, links, and many more than can be listed here. Each is available in a variety of sizes, shapes, and materials, depending on the application. It is important to choose connectors with proper load ratings, because they can easily become points of failure if they do not match the intended load of the system. Two connectors used extensively in this study were shackles and swivels. Shackles are usually steel, and are used to connect lines, buoys, anchors, and vessels. They have three main parts: the body, the bolt, and the cotter pin. Some shackles also have a nut, which helps hold the bolt in place. There are a variety of shackle types and configurations, and Figure 8 shows one similar to those used in this study. Swivels are usually made of steel, and are used to prevent connections from becoming twisted or torqued. A simple swivel is shown in Figure 9.

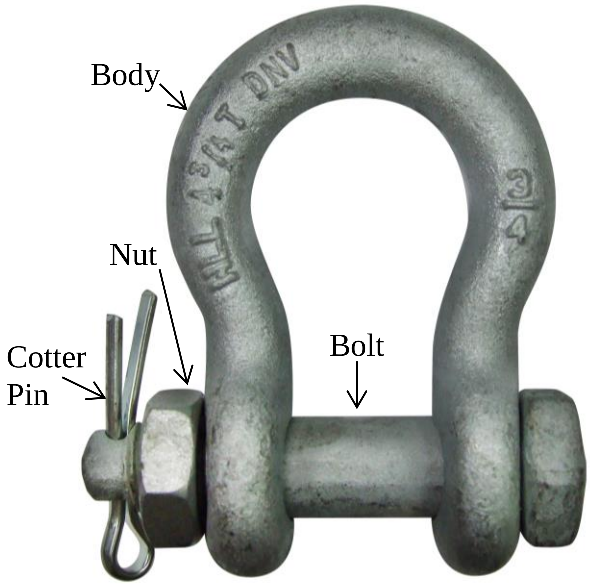

Figure 8: Steel shackle with cotter pin (CMCO 2013)

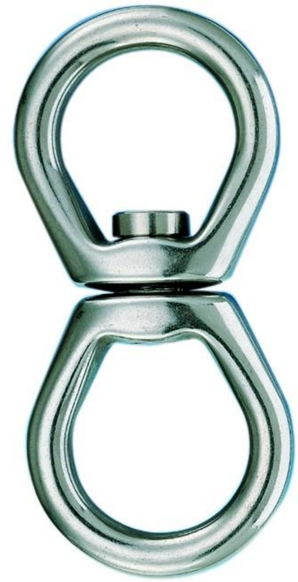

Figure 9: Simple steel swivel (Wichard 2013)

2.1.5 Attachments

There are many types of attachments that can be used in a mooring system. One example is a dead-weight attached to the mooring chain in front of a drag anchor, which helps keep the load horizontal. Another example is when buoyant materials are attached to mooring lines to change their compliance or give them a specific shape. Mooring systems are tailored to the offshore structure they support, and attachments may help to achieve certain characteristics.

2.2 Mooring Configurations

There are many types of mooring configurations used for offshore structures, and they range from simple passive moorings to complex active systems. The three main configuration categories are single-point moorings, spread moorings, and dynamic positioning systems.

Single point moorings utilize one mooring line, and can have one or more anchors. They are often used for deep-water meteorological buoys or small floats. They offer a large amount of compliance for dynamic wave environments, but they have large watch circles and do not provide directional control.

Spread moorings use multiple mooring lines and anchors, and are used to support a wide range of offshore structures. They may have catenary lines, tensioned lines, or a combination of both, and can vary greatly in their complexity. Spread moorings offer directional control and typically have much smaller watch circles than single-points; however, they usually have less compliance and a larger underwater footprint. A spread mooring was used for the Ocean Sentinel mooring system, and examples of typical spread moorings are shown in Figure 10.

Dynamic positioning systems utilize active controls, such as winches or thrusters, to change and control mooring configurations. They can use single point or spread mooring configurations, and are often very complex. Dynamic positioning systems are used for large offshore structures, such as oil-rigs or floating wind turbines. A summary of different mooring configurations and their characteristics is shown in Table 2.

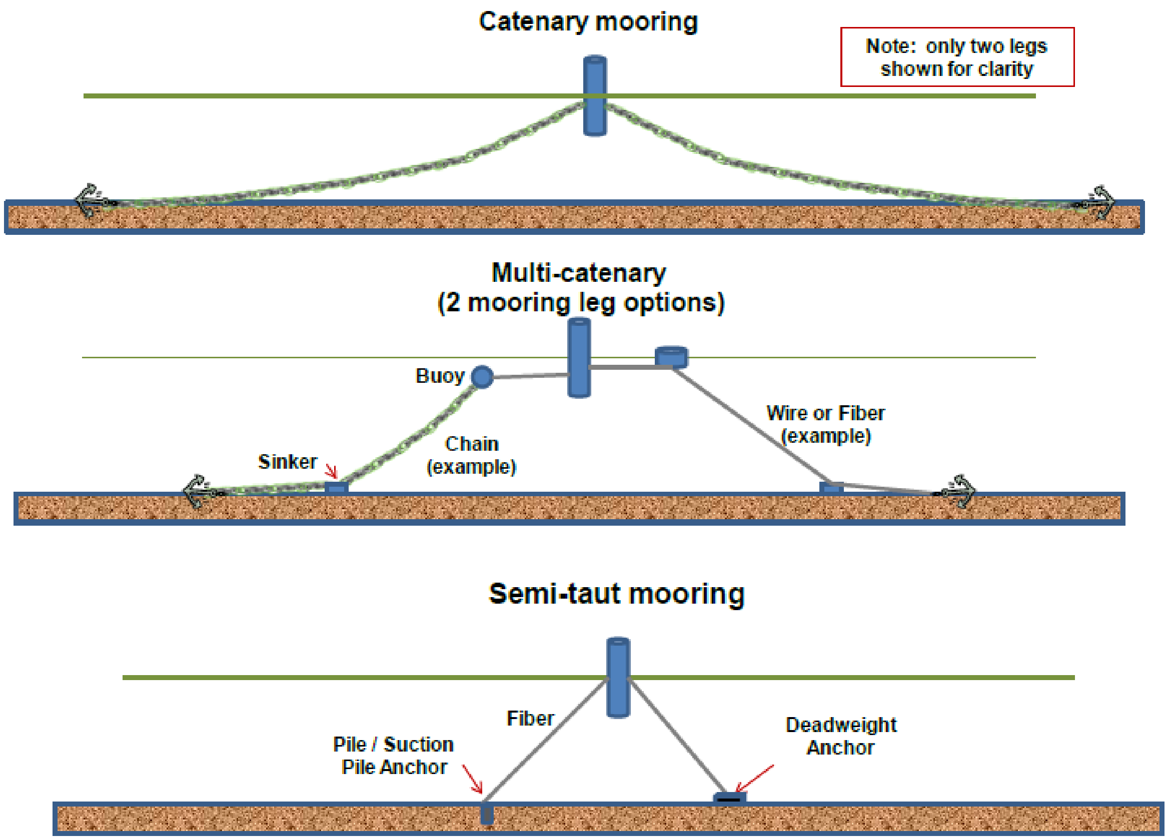

Figure 10: Examples of typical spread mooring systems (SST 2009)

Table 2: Mooring Configuration Comparison and Characteristics (Harris et al. 2004)

Mooring Configuration	**Characteristics**
Spread Moorings	
Catenary Mooring	The mooring lines of a free hanging Catenary Mooring arrive horizontal to the seabed so that the anchor point is only subject to horizontal forces. The restoring forces are mainly generated by the weight of the mooring lines returning the system to equilibrium.
Multi-Catenary Mooring	The catenary mooring lines incorporate weights and buoys to form S- or Wave type configurations. Steep and lazy touch down points are possible.
Taut Spread Mooring (Tethered Mooring)	The mooring lines of a Taut Spread Mooring arrive, typically at an angle to the seabed with the anchor point capable of resisting horizontal and vertical forces. The restoring forces are mainly generated by the elasticity of the mooring line. The mooring lines of a TLP are orthogonal to the seabed, with the restoring force mainly generated by the change in buoyancy of the topside structure.
Single Point Mooring	
Turret Mooring	An internal or external catenary moored turret attached to a floating structure allows weathervaning around the turret.
Catenary Anchor Leg Mooring (CALM)	The floating structure is moored to a catenary moored buoy and is able to weathervane around the moored buoy.
Single Anchor Leg Mooring (SALM)	The floating structure is moored to a single anchored taut buoy and is able to weathervane around the moored buoy.
Articulated Loading Column (ALC)	A moored floating structure can weathervane around a bottom hinged column, which has a swivel above the water line.
Single Point mooring And Reservoir (SPAR)	A catenary anchored SPAR buoy allows the storage of a medium (oil, hydrogen) and a floating structure to weathervane around a mooring point.
Fixed Tower Mooring	A fixed tower anchored into the seabed allows the moored floating structure to weathervane around the mooring point.
Dynamic Positioning	
Active Mooring	The technique for the Active Mooring consist of mooring lines which are spread around the floating structure, where the inboard end of each mooring line is held by a servo controlled winch. A central computer tensions or loosens the mooring lines in order to keep a fixed seabed position.
Propulsion	The technique consists of positioning a floating structure above a fixed seabed point by the use of propellers or thrusters which are controlled from a central computer.

3 Background

3.1 Wave Energy Overview

The United States (US) uses approximately 4,000 terawatt hours of electricity per year, and is increasingly trying to meet this demand with renewable energy sources (US DOE 2013). One such source is wave energy, which harnesses the power of ocean waves to produce electricity. The US is estimated to have 260 terawatt hours of potential wave energy off its coasts (Lettenmaier 2013), with the greatest resource in the Pacific Northwest and Alaska. Figure 11 illustrates this potential wave energy as a function of kw/m of wave crest length.

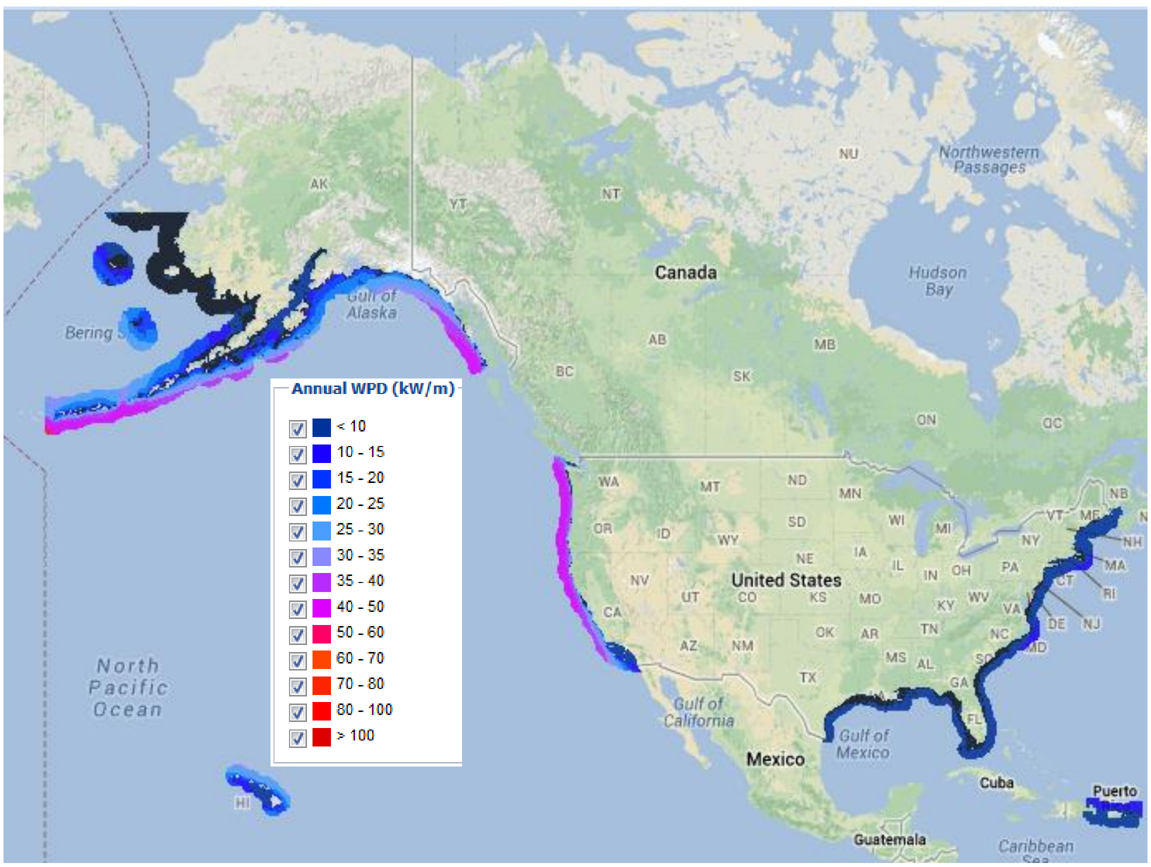

Figure 11: Wave energy potential for the United States (NREL 2013)

Devices that convert wave energy into other forms of energy (e.g. electricity) are called Wave Energy Converters (WEC), and there are three main categories: Oscillating Water

Columns (OWC), Overtopping Devices (OTD), and Wave Activated Buoys (WAB). An OWC uses an internal water column that rises and falls with incoming waves, and pushes air in/out of the device. The moving air spins a Wells turbine, which generates electricity (Figure 12). An OTD uses an elevated water reservoir that is filled each time a large wave passes over. The head difference between the reservoir and sea level is used to spin Kaplan turbines, which produce electricity (Figure 13).

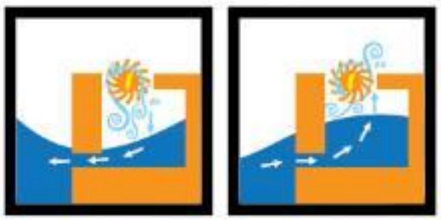

Figure 12: Oscillating Water Column (NNMREC 2013)

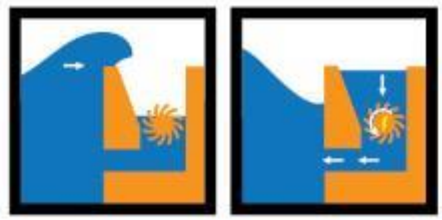

Figure 13: Overtopping Device (NNMREC 2013)

A WAB is a wave activated device that utilizes its motion relative to the sea surface to generate electricity. There are many styles of WAB's currently in development, including Point Absorbers, Attenuators, and Terminators, all of which utilize a variety of power-take-off systems to generate electricity (Figure 14 and Figure 15).

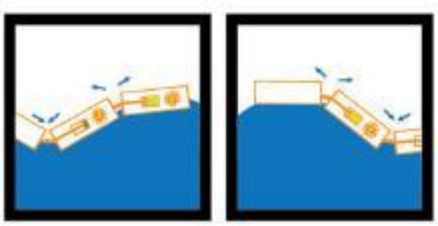

Figure 14: Wave Activated Buoy – Attenuator (NNMREC 2013)

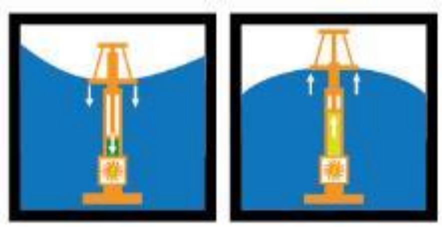

Figure 15: Wave Activated Buoy – Point Absorber (NNMREC 2013)

OWC's and OTD's have typically been developed for near-shore applications and are anchored directly to the seabed, whereas WAB's have primarily been developed for offshore use and utilize mooring systems. Mooring systems for WAB's are often complex, and can have a significant effect on WAB orientation, survivability, and energy extraction (Harris et al. 2004). Although the mooring system in this study was not used to anchor a wave energy device, it is a typical configuration used for WAB's.

3.2 NNMREC

The Northwest National Marine Renewable Energy Center (NNMREC) was established in 2008 as a partnership between Oregon State University (OSU), the University of Washington (UW), and the National Renewable Energy Laboratory (NREL). It is one of three National Marine Renewable Energy Centers funded by the Department of Energy (DOE), with the other two located in Florida and Hawaii. NNMREC's mission is to "support the responsible development of marine and offshore wind energy in the Northwest by:

1. Investigating technical, environmental, and social dimensions of these ocean energy technologies, and carrying out research that fills knowledge gaps
2. Engaging with communities and stakeholder groups to ensure their participation in ocean energy-related decisions in which they have an interest
3. Assisting developers with testing, business planning, and permitting phases" (NNMREC 2013).

OSU's emphasis is on wave energy, while UW primarily focuses on tidal energy. Oregon's coastline has a potential wave power of 12-15 kw/ft (40-50 kw/m) of wave crest length (NREL 2013), making Oregon a premier location for wave energy testing and future development. NNMREC has a number of test facilities in Oregon to accommodate different stages of WEC development, including: the Wallace Energy Systems and Renewable Facility, the O.H. Hinsdale Wave Research Laboratory, the Newport North Energy Test Site (NETS), and the future Newport South Energy Test Site.

3.3 Test Site

The field observation in this study was conducted at the NETS, which is an open ocean test site for WEC prototypes. Devices are connected to the Ocean Sentinel buoy for all measurements and data recording; there is no grid connection or permanent cable running from the test site to shore (this will be part of the South Energy Test Site).

Testing at the NETS is conducted during the summer months, which is typically the most benign wave climate on the Oregon coast. It is located just northwest of Yaquina Head near Newport, OR, and is between 2 – 3 nm (3.7 – 5.6 km) offshore. The entire site encompasses 1 nm^2 (3.5 km^2), but the deployment occupied only a small area in the northeast corner, approximately 0.19 x 0.13 nm (350 x 250 m), shown in Figure 16.

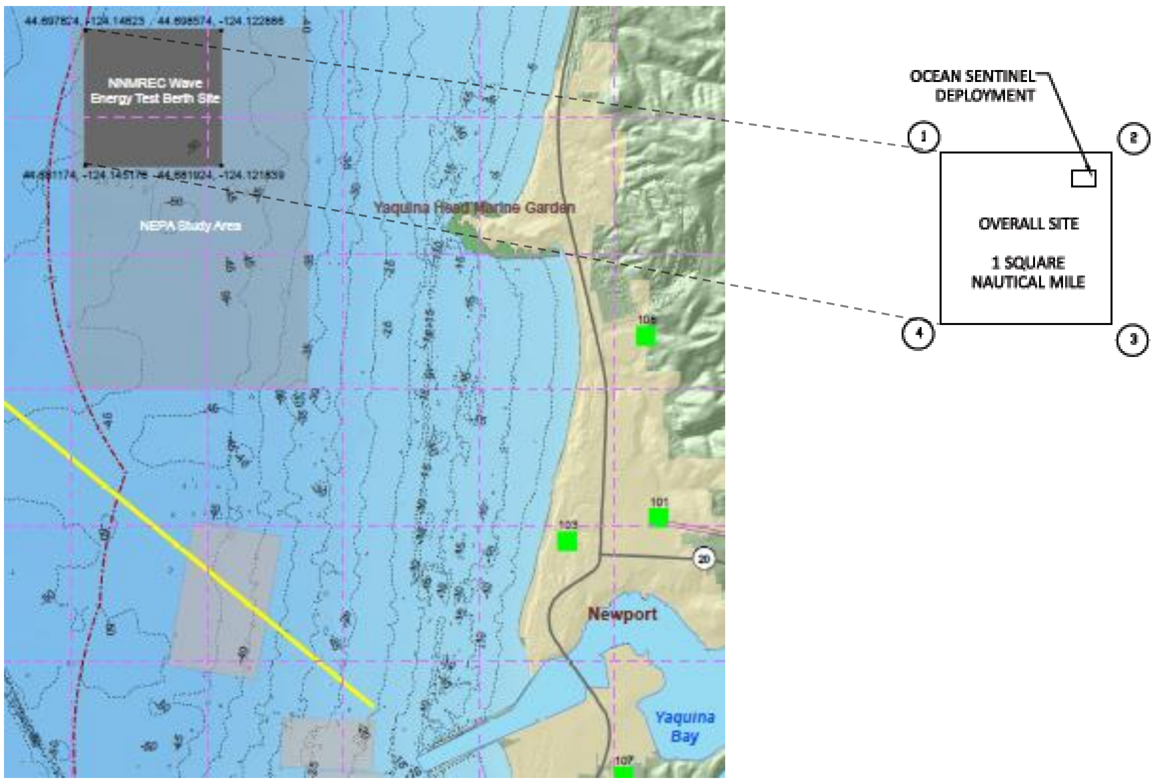

Figure 16: Newport North Energy Test Site (OSU 2011)

The seabed in the deployment location is sandy, gently sloping, and approximately 154 ft (47 m) deep. Surface currents during the summer (Jul – Sep) are approximately 0.5 – 3.5 ft/s (0.15 – 1.1 m/s), and typically run north-to-south or vice versa (CEOAS OSU 2013)[1]. The average significant wave height during the summer is 5.1 ft, with an average dominant wave period of 9.0 s, and an average dominant wave direction of 295.3°. The

[1] All surface current data were from the OSU Ocean Currents Mapping Lab, and recorded with High Frequency RADAR. Data are available from 1999-2013, but not all years include the Newport area. Currents are presented as 1-day averages in ASCII and map format. Surface current numbers given above are an approximation; actual currents and direction are available for individual days.

average wind speed during the summer is 16.3 ft/s (5.0 m/s), with an average wind direction of 196.2° (NOAA 2013)[2].

Storms and swells can bring larger wave events toward the end of the summer. The maximum summer wave height from 2003 – 2012 was 36.1 ft (11.0 m), which occurred on September 27th 2011. The dominant wave period at the time was 14.81 s, and the dominant wave direction was 269° (NOAA 2013). The surface current during this time was 0.6 ft/s (0.2 m/s), and was flowing south-to-north at 14.1° (CEOAS OSU 2013).

3.4 Field Observation Components

3.4.1 Ocean Sentinel Buoy

The Ocean Sentinel is a mobile test platform that was procured by NNMREC for use at the NETS. It is designed to measure electrical output of WEC prototypes up to 100 kW, as well as local environmental conditions. WEC's are connected to the Ocean Sentinel with an umbilical cable, which transfers all generated electricity to the Ocean Sentinel. Wave and current data are recorded by the TRIAXYS buoy, which is transmitted to the Ocean Sentinel via radio link. Other environmental and operational data are recorded onboard the Ocean Sentinel, such as: air temperature, humidity, barometric pressure, and wind speed and direction. Figure 17 shows a typical Ocean Sentinel deployment (Lettenmaier 2013); however, for this study there was no WEC or umbilical cable deployed.

[2] All wave and wind data were taken from NDBC 46050 (2003-2012). Direction data for wind and waves are the direction they are coming from. Wave heights were adjusted specifically for the site to include shoaling effects (see calculation in Appendix A.1). All other wind and wave "test site" data have not been adjusted from NDBC 46050.

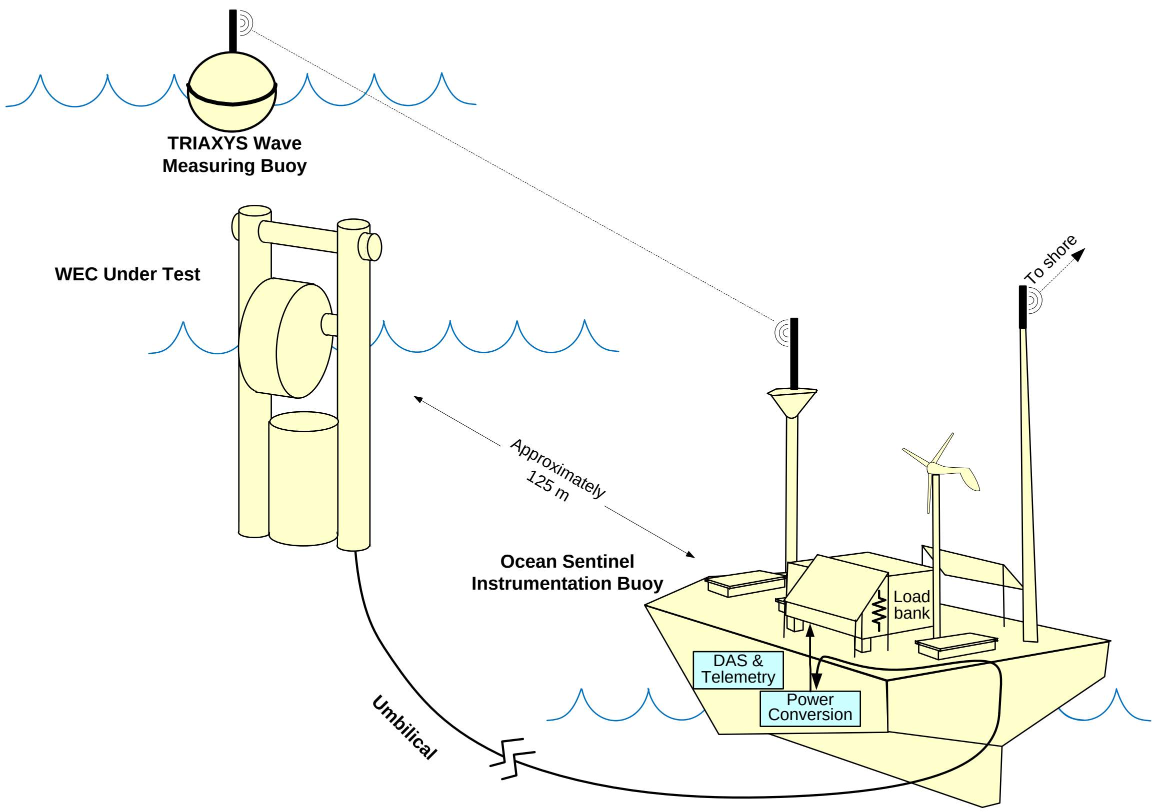

Figure 17: Typical Ocean Sentinel deployment schematic (Lettenmaier 2013)

NNMREC worked with AXYS Technologies to develop the Ocean Sentinel from October 2011 – August 2012. It is a ship-shaped buoy based on the AXYS 6 Meter NOMAD (Navy Oceanographic Meteorological Automatic Device) design, with various modifications for WEC testing (Lettenmaier 2013). AXYS has built and modified NOMAD buoys for various applications, including deep-water meteorological stations and offshore wind assessment platforms. The NOMAD is a proven hull design originally used for the U.S. Navy's offshore data collection program in the 1940's. The U.S. National Data Buoy Center (NDBC) purchased surplus NOMAD's from the Navy for use as meteorological buoys (AXYS 2013), and they are still widely used today from the Bering Sea to the South Pacific (NOAA 2008).

Figure 18: Ocean Sentinel in dry-dock (Hellin 2013-a)

The Ocean Sentinel is 20 ft (6.1 m) long, 10 ft (3 m) wide, and weighs approximately 22,000 lb (10,000 kg) with all equipment and ballast. It has an aluminum hull with four watertight compartments, while the yoke and much of the superstructure are made of steel (AXYS 2013). A list of onboard equipment can be found in *OSU NOMAD Application Manual* (AXYS 2012-b).

3.4.1.1 Environmental Measurements

Primary wind speed and direction are measured using a Vector Instruments A100R/WP200 Anemometer. Data are sampled at 1 Hz, and the range of operation is shown in Table 3. Secondary wind speed and direction are measured with a Gill Windsonic Wind Sensor, which uses ultrasonic transmissions to calculate wind speed and direction. Both instruments are mounted on the Ocean Sentinel's main mast, which is shown in Figure 19 (AXYS 2012-b).

Air temperature and relative humidity are measured using a Rotoronics MP101A, located on the Ocean Sentinel main mast. The sensor's temperature range is -104°F – 140°F (-40°C – 60°C), and its relative humidity range is 0-100% (AXYS 2012-b).

Air pressure is measured using a Vaisala PTB110 barometer located on the Ocean Sentinel main mast (AXYS 2012-b), and its range is 500 – 1100 hPa (Vaisala 2013).

Table 3: Ocean Sentinel Anemometer Range of Operation (AXYS 2012-b)

Vector Anemometer Range of Operation	
Threshold	0.6m/s
Max Speed	>70m/s
Distance Constant	2.3M
Wind Speed Accuracy	0.1m/s (0.7m/s-10m/s) 1% of reading (10-55)m/s 2%>55m/s

Vector Wind Vane Range of Operation	
Threshold	0.75m/s
Max Speed	>75m/s
Response	Damped Natural Wavelength 3.4M
Wind Direction Accuracy	+/- 3% in steady winds greater than 5m/s

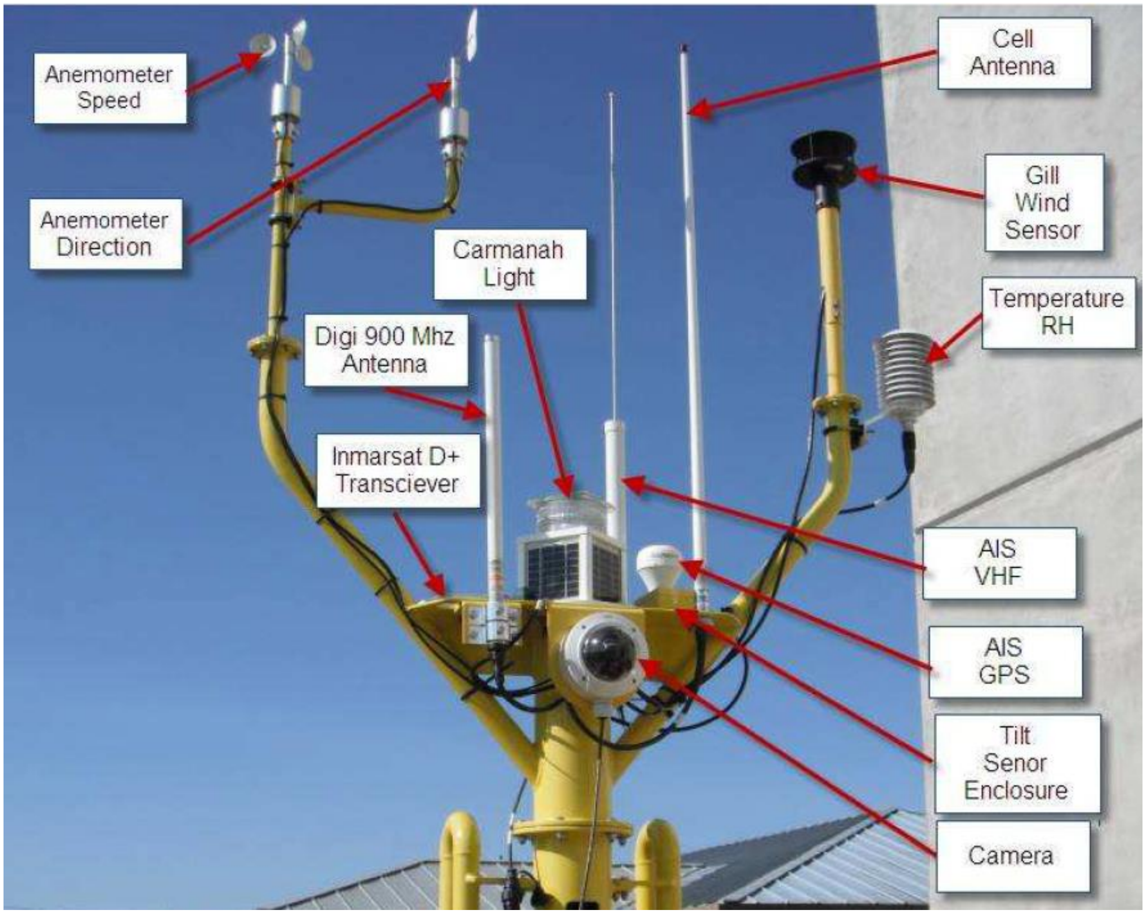

Figure 19: Ocean Sentinel main mast instrumentation (AXYS 2012-b)

3.4.1.2 Data Acquisition Systems

There are two Data Acquisition Systems (DAS) on the Ocean Sentinel: the Watchman 500, and a National Instruments (NI) CompactRIO. The Watchman 500 was provided by AXYS Technologies, and the CompactRIO was purchased and installed by NNMREC. The two DAS are connected via serial link, and each one can communicate independently with shore via 3G cellular telemetry. Dr. Terry Lettenmaier's PhD thesis was used as the main source for this section (Lettenmaier 2013).

3.4.1.2.1 Watchman 500 Data Acquisition System

The Watchman 500 is the standard DAS provided by AXYS with a NOMAD buoy, and it serves three main functions.

1. To monitor and control all of the Ocean Sentinel's onboard systems (power, alarms, sensors, and cameras).
2. To communicate with shore and the TRIAXYS buoy.
3. To monitor and record data from all of the environmental sensors on the Ocean Sentinel and the TRIAXYS buoy.

A full wire diagram for the Watchman 500 DAS is shown in Figure 20.

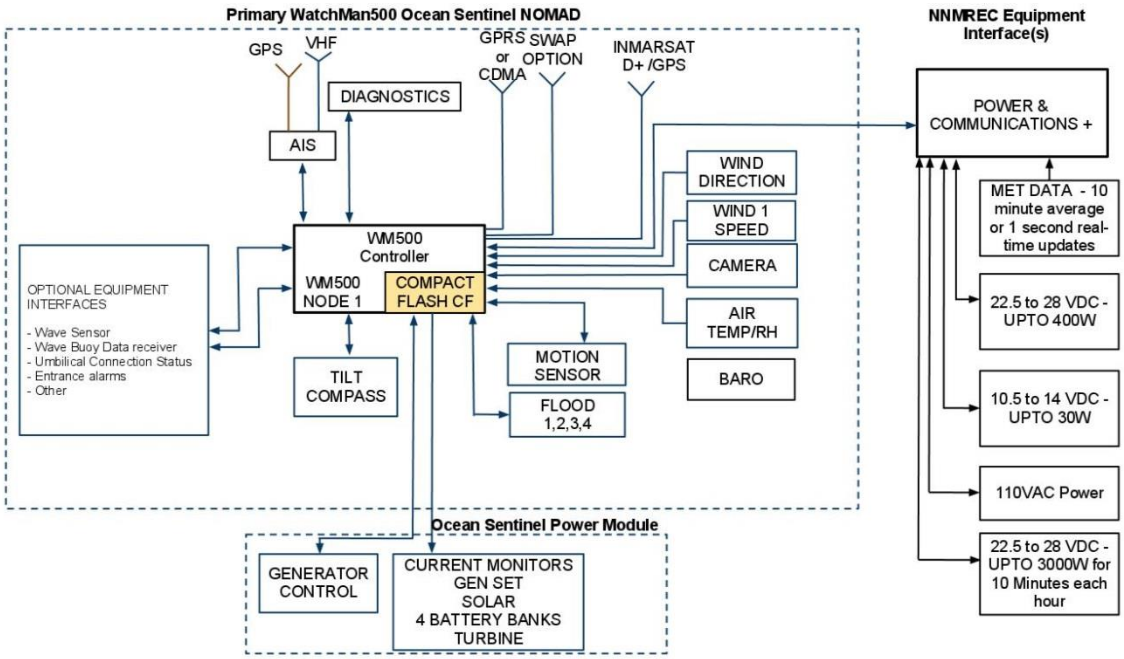

Figure 20: Watchman 500 Data Acquisition System (Lettenmaier 2013)

The Watchman 500 DAS controls the Ocean Sentinel's three power systems: a diesel generator, a wind turbine, and two solar panels. The DAS monitors sensors that detect leaks in the buoy's four compartments, as well as a watch circle alarm that uses GPS to ensure the Ocean Sentinel does not stray too far out of position. The DAS also controls the Ocean Sentinel's two cameras and transmits pictures to shore. One camera is mounted on the main mast and the other on the secondary mast, giving fore and aft views of the Ocean Sentinel and surroundings.

The main telemetry system used by the Watchman 500 DAS for communication to and from shore is the AT&T 3G cellular link. This link transfers data directly to a website hosted and maintained by AXYS Technologies. An INMARSAT D+ satellite communication link is also available as a backup system. The DAS controls the Ocean Sentinel Automatic Identification System (AIS), which sends location and meteorological data to approaching vessels. The DAS also communicates with the TRIAXYS buoy using a 900 MHz radio link.

The Watchman 500 DAS monitors, records, and transmits data from all of the environmental sensors, both onboard the Ocean Sentinel and the TRIAXYS buoy. Air temperature, humidity, barometric pressure, and all wind data are recorded directly by the DAS. Wave, current, and all other ocean data are recorded by the TRIAXYS buoy, and transmitted to the DAS. The DAS packages all of the environmental data into one format and transmits it to shore. These data are transmitted to the CompactRIO via serial link, and also stored onboard. For more detailed information about data formats and transmission cycles, see Section 4.2.

3.4.1.2.2 CompactRIO Data Acquisition System

The NI CompactRIO DAS is a Compact Reconfigurable Input/Output Data Acquisition System that was purchased by NNMREC to record power data and other information transmitted by WEC's being tested. A schematic of the CompactRIO with a typical WEC under test is shown in Figure 21.

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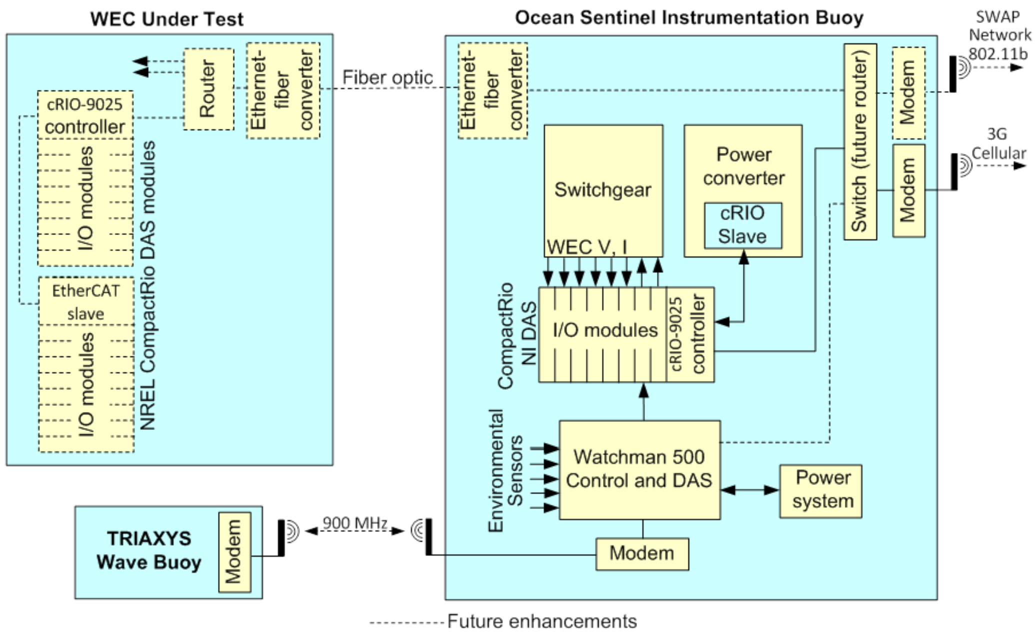


Figure 21: CompactRIO Data Acquisition System (Lettenmaier 2013)

The CompactRIO DAS is controlled and programmed using NI LabVIEW software. For this study there was no WEC being tested; however, the CompactRIO was used to record all mooring line load cell data. This was done by adding a NI9237 module to the DAS, and reprogramming some of the software. Setup, maintenance, and programming of the CompactRIO DAS were done by Dr. Terry Lettenmaier and Dr. Ean Amon.

In this study, both the load cell and environmental data were stored in the CompactRIO DAS until they were downloaded by NNMREC using a Verizon 3G cellular link. For more information on data formats, processing, and transmission cycles, see Section 4.2.

3.4.2 TRIAXYS Buoy

The AXYS TRIAXYS Directional Wave Buoy is a surface following buoy used to measure non-breaking waves and currents. It was procured by NNMREC in 2012 along with the Ocean Sentinel to measure environmental conditions at the NETS. It is usually deployed with the Ocean Sentinel, approximately 450 ft (137 m) away, but it can also be deployed by itself. Statistical data are transmitted to the Ocean Sentinel via 900MHz radio link, while time-series data are stored onboard.

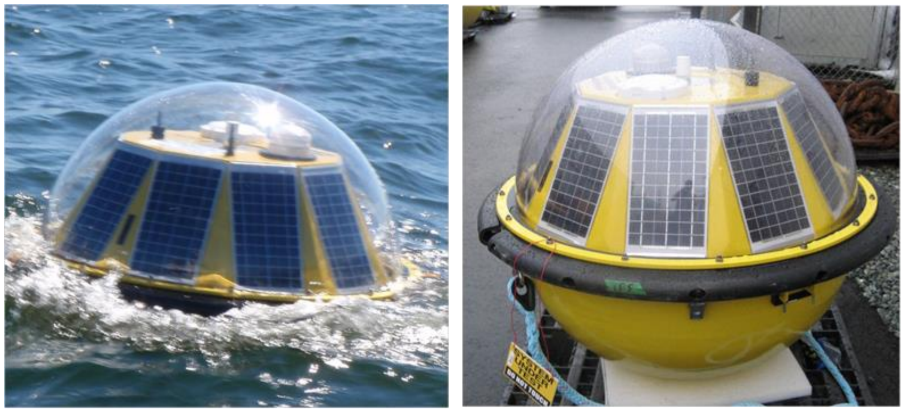


Figure 22: TRIAXYS buoy deployed and dockside (Lettenmaier 2013)

The buoy has a 3.6 ft diameter around the bumper, and weighs approximately 430 lbs. It has ten solar panels and four lead-acid batteries to provide power. Onboard sensors included temperature gages, accelerometers, gyroscopes, a compass, GPS, and an Acoustic Doppler Current Profiler (ADCP). For a complete list of specifications and onboard equipment, see Appendix B (AXYS 2010).

The TRIAXYS buoy produces the following wave data: height, period, and direction, as well as directional and non-directional frequency spectra. To make these measurements, the buoy uses three accelerometers, three rate gyros, and a fluxgate compass, all of which are sampled at 4 Hz. Data from these sensors are fed into the onboard Watchman 500 microprocessor, which uses a Fast Fourier Transform (FFT) based algorithm to solve the full non-linear equations of motion for the buoy in all six degrees of freedom. The algorithm was developed by the Canadian Hydraulics Centre of the National Research Council of Canada (AXYS 2010). The wave measurement time-frame can be set from 1 – 35 minutes, and was set to 20 minutes for this study. For specific wave parameters produced by the TRIAXYS, see Appendix H.2.2 and H.2.4.

The TRIAXYS buoy uses a Nortek 600 kHz Aquadopp ADCP mounted in the bottom of its hull to measure current speed and direction (AXYS 2010). The ADCP uses acoustic transmissions, along with temperature, pressure, tilt, and compass sensors, to measure current throughout the water column. The measurements are taken in layers or "bins" that are 3.28 ft (1 m) deep. The bins overlap, so the current speed and direction is given in 1.64 ft (0.5 m) intervals from 7.05 – 87.46 ft (2.15 – 26.65 m) deep. All of the ADCP data are fed through the onboard Watchman 500 processor, and transmitted to the Ocean Sentinel with the wave data. See Appendix H.2.3 for specific current parameters.

Figure 23: TRIAXYS ADCP (AXYS 2010)

3.4.3 AWAC

A 600 kHz Nortek Acoustic Wave and Current Profiler (AWAC) was procured by NNMREC and used during the 2013 deployment as an independent source for wave and current data. It was setup in “stand-alone” mode for the deployment, where all data were stored onboard and not available until the device was recovered. The device was mounted in a custom bottom-lander frame (see Figure 24), which housed the AWAC, battery pack, recovery float, and anchor weight. The complete package weighed approximately 400 lb (182 kg), and detailed specifications for the AWAC can be found in Appendix C. Data from the AWAC were not used in this study because it was not processed or analyzed in time.

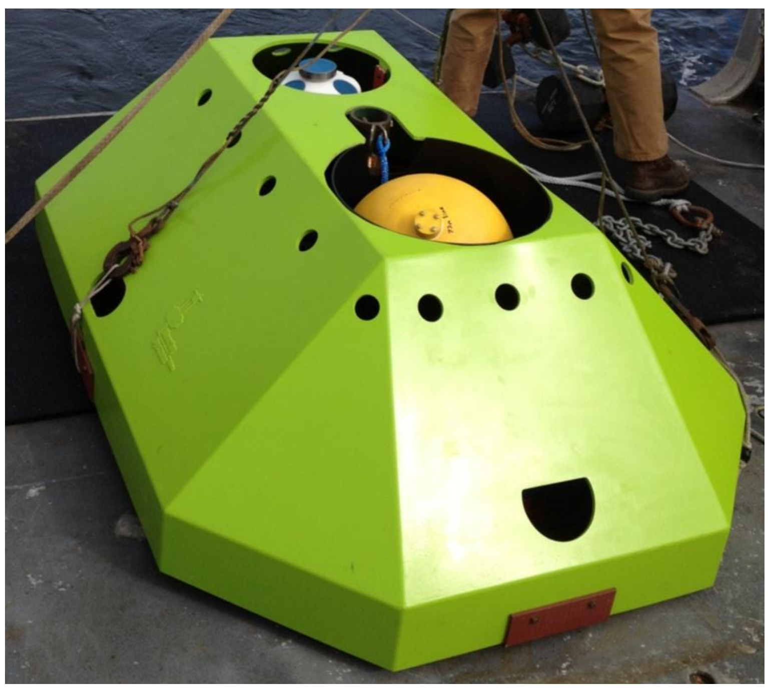


Figure 24: AWAC mounted in custom bottom-lander frame

The AWAC measures waves using acoustic transmissions. It also has a pressure transducer capable of measuring tides or waves under ice. Wave height and period are measured with the center transducer using Acoustic Surface Tracking (AST) technology. Wave direction is measured with orbital velocity measurements near the surface from the three side transducers, combined with the AST measurement. This four-point array is processed using a maximum likelihood method to calculate directional wave spectra (Nortek 2013).

The AWAC measures current with the three side transducers (Nortek 2013).

3.5 Numerical Modeling Software

OrcaFlex is a marine design software package used for static and dynamic analysis of offshore systems. It was first developed by Orcina Ltd in 1986, and has undergone various revisions and updates since. OrcaFlex is used in industry to analyze various types of marine systems, from buoys and ship motions, to moorings and underwater pipelines. It is a fully non-linear time domain finite element program with a 3D graphical user interface. Objects are constructed using lumped mass elements, which greatly simplifies calculations and allows for reduced processing time. It is also capable of dealing with large deflections of components, which makes it especially useful for analyzing mooring lines. In addition, modal analysis can be performed for individual lines, or an entire system. Specifics about OrcaFlex theory relevant to this study can be found in Appendix J (Orcina 2012).

OrcaFlex was used by 3U Technologies to build a model of the Ocean Sentinel and its mooring system prior to the 2012 deployment. This model was used as the starting point for constructing the model in this study. OrcaFlex was also recently used at OSU for WEC modeling and simulations (Lettenmaier 2013).

4 Field Observation

4.1 Ocean Sentinel Mooring System

The Ocean Sentinel used a three-point mooring system with gravity anchors and surface floats. The system was intended to serve three main functions:

1. Keep the Ocean Sentinel on station, and ensure its survivability
2. Keep the Ocean Sentinel in a controlled watch circle, ensuring umbilical design parameters are maintained

3. Control the Ocean Sentinel heading, and keep the umbilical power cable from twisting or becoming tangled.

4.1.1 Design

The Ocean Sentinel mooring system went through three design iterations before the buoy was first deployed in 2012, which are discussed below.

4.1.1.1 Initial Design

AXYS Technologies designed the initial Ocean Sentinel mooring system, which was the first three-point mooring system used for one of their NOMAD buoys. Typically, their NOMAD buoys are deployed with single point mooring systems in deep water, an example of which is shown in Appendix D.1.

The AXYS three-point design was a slack mooring system with ample compliance to give the Ocean Sentinel similar wave-riding characteristics to a single-point mooring, but with directional control and a tighter watch circle. This design specified the use of three concrete gravity anchors, three steel surface buoys, three steel mooring chains from the anchors to the surface buoys, and three polyester mooring lines from the buoys to the Ocean Sentinel. Schematics of this mooring design, as well as the anchor specifications, are shown in Appendix D.2 and D.3, respectively.

4.1.1.2 1st Design Optimization

Sound and Sea Technology Engineering Solutions (SST) was hired by NNMREC to perform a third-party review of the initial Ocean Sentinel mooring system design, and to provide recommendations for optimization alternatives. SST utilized inputs provided by AXYS to build a numerical model of the Ocean Sentinel buoy and its mooring system using AQWA. SST ran simulations based on operational and extreme environmental conditions at the NETS for the Ocean Sentinel, the WET-NZ, and the two devices coupled together with the umbilical power cable. SST found that the Ocean Sentinel performed well in large wave climates, but the bow anchor experienced forces very close to the uplift capacity, with large snap-loads. The Ocean Sentinel also had poor directional control and a large watch circle in calmer seas, causing the umbilical to become tangled with the mooring lines.

SST had three major recommendations for improving the mooring system.

1. Redesign the bow mooring leg, including:
    a. Change the bow anchor from a concrete gravity anchor to a drag anchor
    b. Add 164 ft (50 m) of anchor chain
    c. Add a 500 lb (227 kg) sinker weight in front of the drag anchor

    These changes were intended to add more holding capacity to the bow anchor and make loading smoother to reduce snap-loads.
2. Shorten each polyester mooring line by approximately 50 ft (15 m), which would tighten the watch circle and prevent umbilical entanglement.
3. Move the Ocean Sentinel approximately 164 ft (50 m) further away from the WET-NZ. This would reduce slack in the umbilical and the possibility of buoy collision.

Diagrams of these recommendations are shown in Appendix E, and additional SST recommendations can be found in *Ocean Sentinel: Oregon Mooring Assessment* (SST 2012).

4.1.1.3 2nd Design Optimization

3U Technologies was hired by NNMREC to complete a comprehensive design and analysis of the 100 kW umbilical power cable, and show how it affected the mooring systems of both the Ocean Sentinel and the WET-NZ. 3U used OrcaFlex to build detailed models of the Ocean Sentinel, the WET-NZ, both mooring systems, and the umbilical. Simulations were run for operational and extreme environmental conditions with a focus on umbilical cable position, loads, bending, and stress. Results and recommendations were provided for umbilical cable routing, length, shape, and connections. 3U also provided all of the OrcaFlex models to NNMREC as part of their deliverables.

3U used information from SST and AXYS to build the Ocean Sentinel model in OrcaFlex, which included: environmental information for the NETS, detailed information about the Ocean Sentinel and its mooring system, mooring line manufacturers' data, anchor properties, and buoy information. SST provided RAO data for the Ocean Sentinel, which was calculated using AQWA. AXYS also provided the as-delivered weight and center-of-gravity for the Ocean Sentinel and its yoke.

The Ocean Sentinel model was based on the AXYS mooring design with SST recommendations. It included three steel mooring chains, three steel surface buoys, three polyester mooring lines, and the Ocean Sentinel buoy. The concrete anchors were not modeled, so the mooring chains were anchored directly to the seabed. Component connections were as follows:

- The port and starboard anchor chains were 177 ft (54m) long, and were connected directly from the seafloor to the port and starboard surface buoys.
- The bow mooring chain was 341 ft (104 m) long, and was connected from the seabed to the bow surface buoy, with a clump weight attachment of 500 lb (227 kg) at 164 ft (50 m) from the anchored position.
- All of the polyester mooring lines were 279 ft (85 m) long, and connected from the surface buoys to the Ocean Sentinel.
    - The port and starboard polyester mooring lines were connected to the aft corners of the Ocean Sentinel
    - The bow polyester mooring line was connected to the yoke.

4.1.2 Deployed Configurations

4.1.2.1 2012

The Ocean Sentinel was deployed in 2012 with a three-point mooring system, with three:

- 4-ton (3.6 tonne) concrete gravity anchors
- 58 in (147 cm) steel surface buoys
- 1 in (2.5 cm) steel mooring chains

- 1.5 in (3.8 cm) polyester mooring lines.

The anchors were setup in a triangular geometry, with approximately 120° between each leg (Figure 25). Distances of each leg were as follows:

- Bow anchor: 140 ft (43 m) from the “equilibrium-position” of the Ocean Sentinel
- Port/starboard anchors: 102 ft (31 m) from the “equilibrium-position” of the Ocean Sentinel

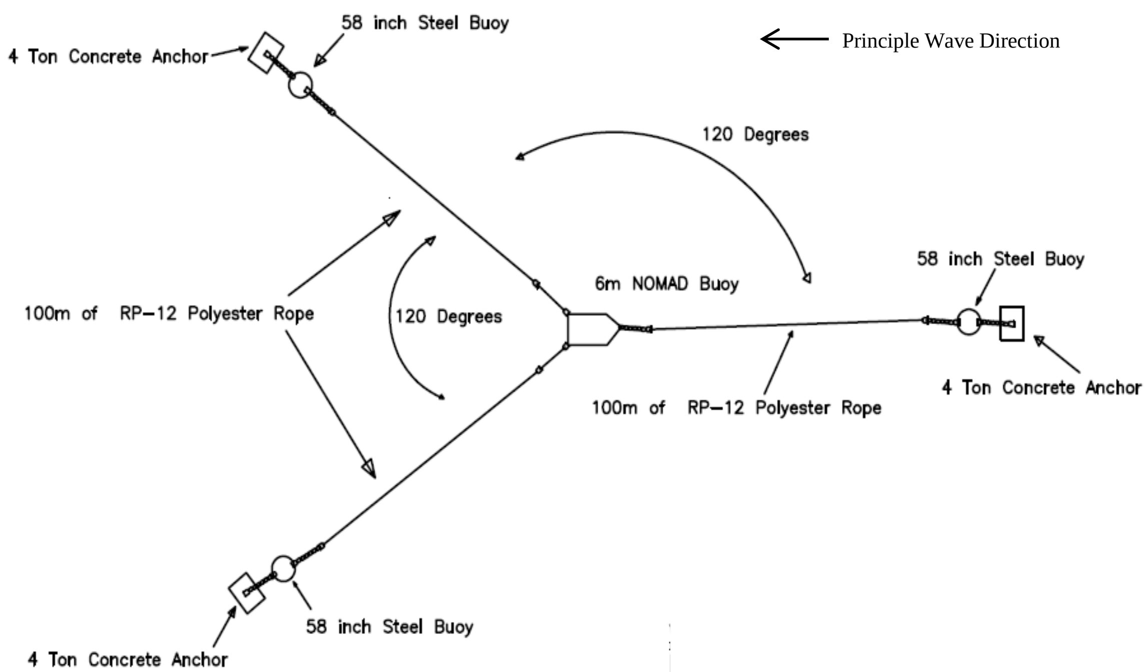


Figure 25: Ocean Sentinel general mooring layout (AXYS 2012-c)

The mooring chains, surface buoys, and mooring lines on each leg were linked to a steel connecting ring located 3.28 ft (1 m) below each surface buoy (Figure 29). The rings were connected to the:

- Surface buoys with 3.28 ft (1 m) of 1 in (2.5 cm) chain
- Mooring lines with 13 ft (4 m) of 1 in (2.5 cm) chain
- Mooring chains directly.

On the bow leg, there was:

- 270 ft (82 m) of mooring chain from the anchor to the connecting ring
- 233 ft (71 m) of mooring line from the connecting ring chain to 33 ft (10 m) of 1 in (2.5 cm) chain, which was connected directly to the yoke.

On the port and starboard legs, there was:

- 180 ft (55 m) of mooring chain from the anchors to the connecting rings
- 266 ft (81 m) of mooring line from the connecting ring chains to the Ocean Sentinel aft connection points.

The 2012 mooring configuration included SST's recommendation to shorten the mooring lines, but not the bow leg anchor recommendations. Constructing a new anchor and a 500 lb (227 kg) sinker weight would have increased planning time and deployment requirements beyond what was available at the time.

See Appendix F for the 2012 deployment layout with all buoys, devices, and GPS coordinates (actual deployed anchor coordinates were slightly different).

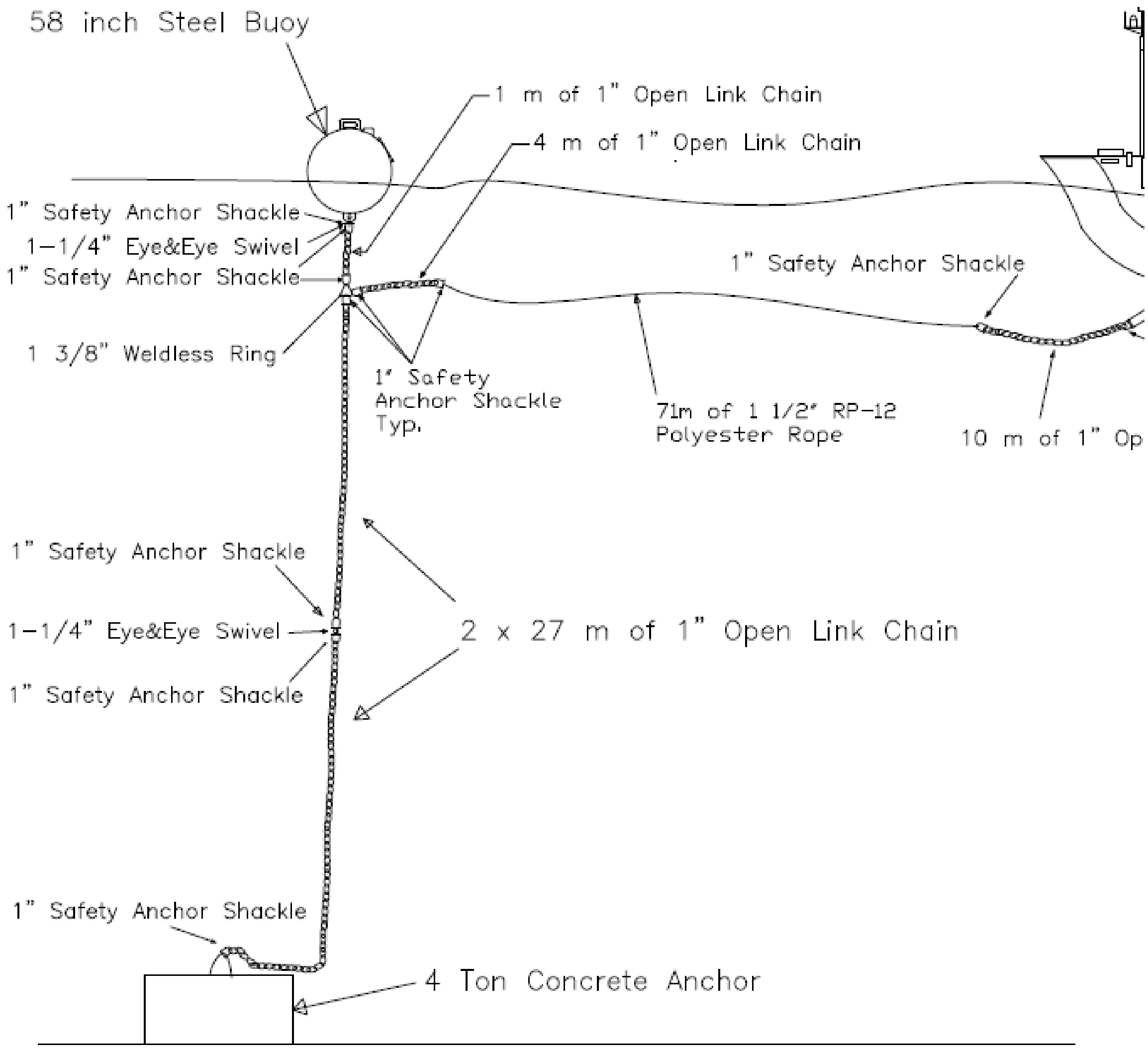


Figure 26: Bow mooring leg connection details, 2012 configuration (AXYS 2012-c)

4.1.2.2 2013

The layout for the 2013 deployment was very similar to the 2012 deployment, with some modifications. The Ocean Sentinel and all of its anchors, as well as all of the corner marker buoys, had the same planned GPS coordinates as the 2012 deployment. The TRIAXYS buoy was moved to a new GPS location, and the AWAC was new for 2013. The layout and GPS coordinates are shown in Figure 27.

The 13 ft (4 m) of chain that connected each steel connecting ring to the mooring lines in 2012 was replaced with 13 ft (4 m) of 1 in (2.5 cm) spectra line. During deployment, the spectra lines were secured from the connecting rings to the top of the surface buoys, which allowed for easier mooring line connections. The spectra line reduced wear on the surface buoys during this time (in comparison to chain), and were cut during recovery operations to quickly disconnect the mooring lines from the surface buoys.

Two new additions to the mooring system for 2013 were load cells and swivels. There were two load cells placed in series on the bow leg for redundancy, and one load cell on the port and starboard legs. One swivel was placed on each mooring line below the load cells to ensure the lines did not torque the load cells.

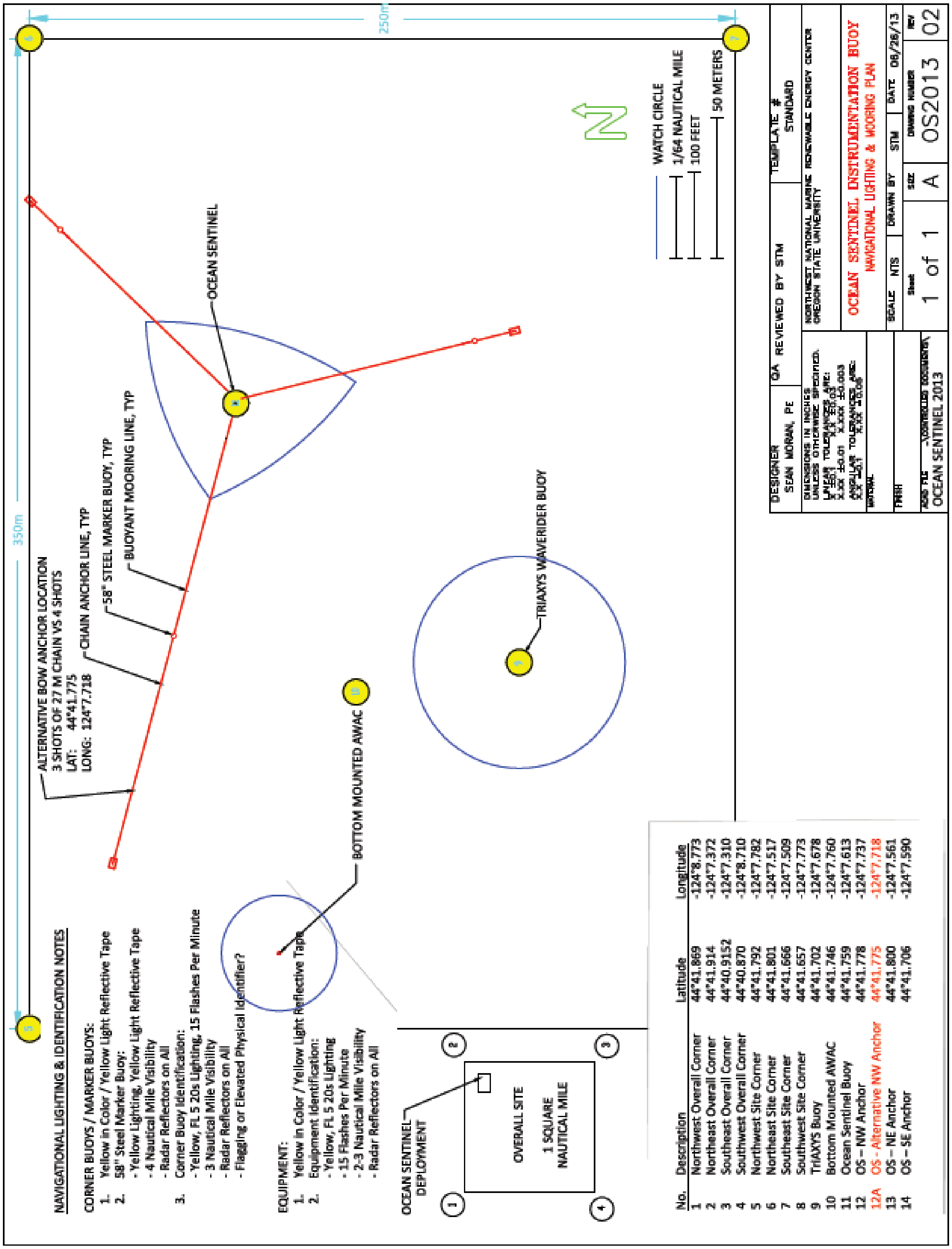


Figure 27: 2013 Ocean Sentinel Deployment Layout

4.1.3 Components

4.1.3.1 Mooring Lines

Mooring lines were 1.5 in (3.8 cm) Samson RP-12 SSR 1200. This is a twelve-strand synthetic line manufactured with polyester wrapped around Ultra Blue fiber.

Table 4: Mooring Line Specifications (Samson 2013-a)

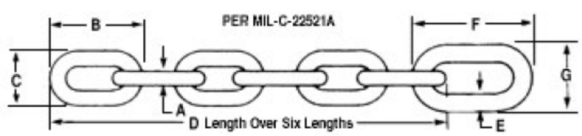
DIAM. (inch)	CIRC. (inch)	WEIGHT PER 100 FT. (lbs)	AVG. STRENGTH (lbs)	MIN. STRENGTH (lbs)
1 1/2"	4 1/2"	60.0	60,000	54,000

4.1.3.2 Chain

Mooring and connecting chains were 1 in (2.5 cm) open-link steel chain.

OPEN-LINK CHAIN - COAST GUARD BUOY CHAIN SPECIFICATIONS

All Specifications in pounds and inches unless otherwise indicated.



Common Links					End Links					Weight Per 15-Fathom Shot (Apprx.)
Wire Diameter - A -		Length - B -	Width - C -	Length Over Six Lengths - D -	Wire Diameter - E -	Length - F -	Width - G -	Proof Test	Break Test	
Inches	mm									
1/2	13	3	1-7/8	13	3/4	4-1/4	2-5/8	7500	15000	210
5/8	16	3-3/4	2-1/4	16-1/4	3/4	4-1/2	2-5/8	11500	23000	323
3/4	19	4-1/2	2-5/8	19-1/2	7/8	5-1/4	3-1/8	16000	32000	442
7/8	22	5-1/4	3-1/8	22-3/4	1-1/8	6-3/4	3-7/8	22000	40000	608
1	25	6	3-1/2	26	1-1/4	7-1/2	4-3/8	29000	58000	780

Figure 28: Mooring and Connecting Chain Specifications (SST 2012)

4.1.3.3 Anchors

The anchors were 4 x 4 x 4 ft (1.2 x 1.2 x 1.2 m) concrete blocks that weighed approximately 4 tons (3.6 tonne), and were cast at the OSU Ship Operations Facility (Ship Ops). See Appendix D.3 for details. A concrete mix design from similar marine applications in the Newport area was used, and the anchors had approximately 5000 lb (2273 kg) of "in-water weight" (see Appendix A.2).

Figure 29: Concrete Anchor Construction (Moran 2011)

4.1.3.4 Surface Buoys

The surface buoys were 58 in (147 cm) hollow steel spheres. They allowed surface connection of the mooring chains and lines, served as markers for the anchors, and helped facilitate anchor recovery. For the 2013 deployment, 3 ft (0.9 m) steel masts were welded onto the top of each buoy to increase visibility on the water. On top of each mast were a navigational light and a radar reflector, to comply with US Coast Guard requirements.

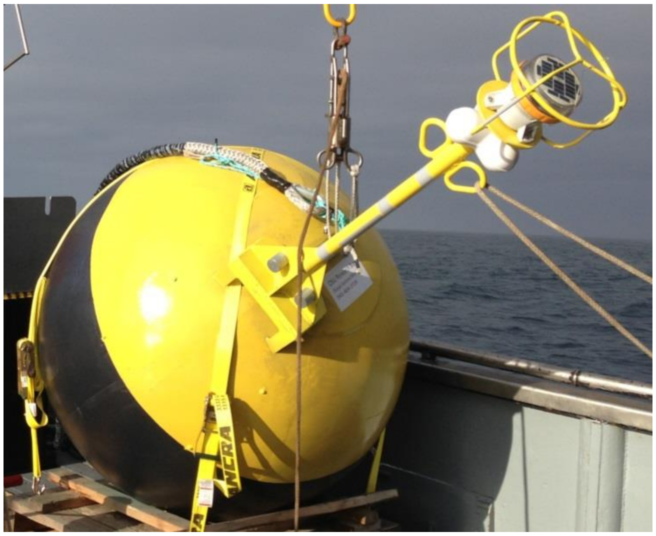


Figure 30: Surface Buoy

4.1.3.5 Connectors

4.1.3.5.1 Shackles

Shackles were used during the deployment to connect mooring components (lines to lines, lines to buoys, load cells to swivels, etc). Steel shackles were used with bolts, nuts, and cotter pins (except for the yoke shackle, which had no nut). All of the shackles were 1 in (2.5 cm), except for the yoke shackle (1.5 in, 3.8 cm) and load cell shackles (7/8 in, 2.2 cm). The shackles connecting the port and starboard mooring lines to the Ocean Sentinel had rubber gaskets to prevent galvanic corrosion with the aluminum hull.

4.1.3.5.2 Spectra Line

Three 13 ft (4 m) sections of 1 in (2.5 cm) spectra line were used during the 2013 deployment to connect the mooring lines to the steel connector rings beneath the surface buoys. The spectra line was Samson AmSteel, with twelve strands of Dyneema fiber.

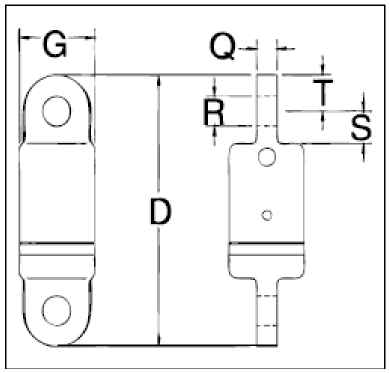
Table 5: Spectra Line Specifications (Samson 2013-b)

DIAM. (inch)	CIRC. (inch)	WEIGHT PER 100 FT. (lbs)	AVG. STRENGTH (lbs)	MIN. STRENGTH (lbs)
1"	3"	21.8	90,000	81,000

4.1.3.5.3 Swivels

The swivels used were Crosby 10-S-5 swivels rated to 11 ton (10 tonne), and each one weighed 42 lb (19 kg). One swivel was attached to each mooring line below the load cells.

Table 6: Swivel Specifications (Crosby 2013)



Swivel No.	S-5 Stock No.	Working Load Limit (t)*	Wire Rope Size (in.)	Weight Each (lbs.)	Dimensions (in.)					
					D	G	Q	R	S	T
3-S-5	297057	3	1/2	8.50	9.41	2.75	.75	1.03	1.12	1.25
5-S-5	297253	5	5/8	11.30	9.81	3.00	1.00	1.28	1.25	1.25
8-S-5	297459	8-1/2	3/4	29.25	11.88	4.00	1.25	1.41	1.62	1.50
10-S-5	297654	10	7/8	42.00	15.50	4.50	1.69	1.69	2.75	1.88
15-S-5	297850	15	1	49.00	16.38	5.00	1.94	2.03	2.75	2.12
25-S-5	298154	25	-	130.00	22.25	6.00	2.25	2.31	3.88	2.38
35-S-5	298252	35	-	145.00	22.25	6.50	2.25	2.31	3.88	2.38
45-S-5	298350	45	-	215.00	26.50	7.00	2.50	2.53	4.00	3.00

*Individually Proof Tested to 2 times the Working Load Limit. Ultimate Load is 5 times the Working Load Limit.

4.1.3.6 Load Cells

4.1.3.6.1 Purpose

Load cells were added to the 2013 Ocean Sentinel Deployment to measure forces in the Ocean Sentinel mooring lines. The load cells were only designed to measure tension, and did not measure compression or torsion. Each load cell was rated to 10,000 lb (44.48 kN), with safe working loads up to 15,000 lb (66.72 kN).

4.1.3.6.2 Theory

Each load cell measured force using strain gages configured in a full Wheatstone bridge. Strain is the amount of deflection that a material undergoes when a force is applied

(Figure 31). It is a dimensionless quantity usually expressed in units of length/length (Equation 1). Axial strain is directly related to stress through Young's Modulus (Equation 2), which is directly related to the applied force (Equation 3).

$$\boldsymbol{\varepsilon} = \frac{\Delta \boldsymbol{L}}{\boldsymbol{L}} \tag{1}$$

$$\sigma = \varepsilon E = \frac{F}{A} \tag{2}$$

$$F = \varepsilon E A \tag{3}$$

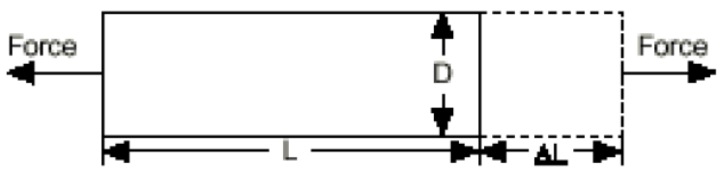


Figure 31: Strain diagram (NI 2013-a)

Strain gages use a specific type of material where the electrical resistance changes when the material is strained. Strain is directly proportional to the voltage measured, which allows for calculation of the force during each measurement. Typically this change in resistance is very small, so strain gages are often configured into a Wheatstone bridge with an excitation voltage to improve measurability. The measured voltage change is a function of the excitation voltage.

$$V_o = \left[\frac{R_3}{R_3+R_4} - \frac{R_2}{R_1+R_2}\right] V_{EX} \tag{4}$$

Wheatstone bridges are typically setup as a full bridge, where all of the resistors are active strain gages (see Figure 32).

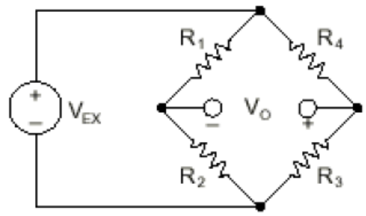


Figure 32: Wheatstone bridge (NI 2013-a)

They can also be setup as quarter or half bridges, where only one or two of the resistors are active strain gages, respectively. Full bridges help minimize measurement errors due to thermal expansion, and improve bridge sensitivity (NI 2013-a).

4.1.3.6.3 Procurement

Five load cells were procured from Sensing Systems Corporation, New Bedford, MA, on June 11th 2013. They were custom built and quoted with a six week lead time. They arrived on July 17th 2013.

4.1.3.6.4 Specifications (SSC 2013)

Capacity:	10,000 lb (44.48 kN)
Max Safe Load:	15,000 lb (66.72 kN)
Output Voltage:	1.5 mV/V (at rated capacity)
Calibration:	National Institute of Standards (NIST) certificate
Accuracy/Combined Errors:	25 lb (0.11 kN)
Material:	17-4 PH stainless steel
Cable/Connector:	SubConn MCBH5FSS
Load Cell Size:	Diameter: 3 in (7.6 cm), Length: 11 in (28 cm)
Shackle Compatibility:	7/8 in (2.2 cm)

An excitation voltage of 3.3 V was used in this study, which gave an output voltage of 4.95×10^{-7} V/lb (1.11×10^{-4} V/kN) for each load cell. The sampling rate for each load cell used in this study was 20 Hz, which provided a good balance between desired resolution and data storage capacity onboard the Ocean Sentinel.

4.1.3.6.5 Integration

The load cells were connected directly to the three mooring lines. For the port and starboard mooring lines, there was one load cell connected directly to the Ocean Sentinel at the aft connection points (Figure 33). For the bow mooring line two load cells were used in series for redundancy, which were connected directly to the yoke (Figure 34). They were installed well below the water-line, which would make them difficult to service during the deployment if a failure occurred.

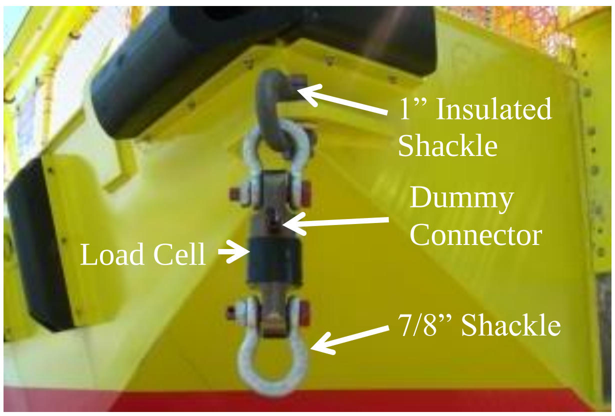


Figure 33: Port load cell attached to the rear connection point

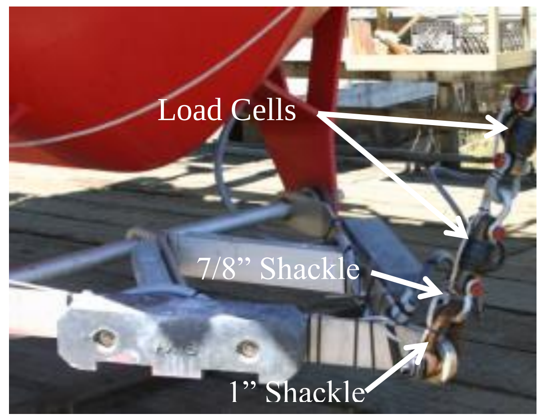


Figure 34: Bow load cells attached to the yoke (Hellin 2013-a)

The load cells were connected to the CompactRIO DAS with 30 – 50 ft (9.1 – 15.2 m) of SubConn MCIL5M 20-5 cable. The cable was run through plastic conduit for protection during the deployment. For the Bow load cells, the cable was run first through ½ in (1.3 cm) conduit, and then through 1 in (2.5 cm) conduit for double protection from abrasion and impact. The conduit for each load cell was routed along different sides of the Ocean Sentinel for redundancy; they ran along both sides of the yoke, up the port and starboard sides of the hull, through the first bumper, and then along the deck to the junction box (Figure 35). For the port and starboard load cells, the cable was run through ½ in (1.3 cm) conduit, which was routed through the adjacent horizontal bumper, then through a short piece of 1 in (2.5 cm) conduit up to the deck, and along the deck to the junction box (Figure 36). All of the cables entered the junction box through watertight glands, and were then routed into the forward compartment to the CompactRIO DAS (Figure 37).

Figure 35: Bow load cell cable routing along the yoke and hull (Hellin 2013-a).

Figure 36: Port load cell cable routing (Moran 2013).

Figure 37: Junction box with watertight gland (Moran 2013).

4.1.3.6.6 Calibration

The load cells were calibrated by the manufacturer, and each one came with an NIST certificate; however, the team felt it was necessary to test them before deployment. First, a shunt calibration was performed on each load cell, which is an electronic test using a known resistor. Second, small known weights were placed on the port and starboard load cells (body weight of 1-2 people), to ensure the DAS was communicating with the load cells. Third, a known load cell was placed in line with the bow load cells, and the yoke and chain were lifted from above. The known load cell was a 10,000 lb (44.48 kN) Dillon EDxtreme. Fourth, the known load cell was placed in line with the starboard load cell, and a 600 lb railroad wheel was hung from them (Figure 38). The starboard load cell measurement was within 0.16% of the Dillon EDxtreme. For complete calibration results see Appendix G.

Figure 38: Starboard load cell calibration

4.2 Data Acquisition

4.2.1 Data Recording and Transmission

The CompactRIO was used as the primary DAS in this study for acquiring and transmitting load cell and environmental data. The data were downloaded from the CompactRIO to a host computer on shore using File Transfer Protocol (FTP) over the Verizon 3G cellular link. In addition, the data could be viewed in real time using the LabVIEW host user interface software (see Figure 39). Environmental data recorded by the AXYS Watchman 500 DAS were independently transferred via the AT&T 3G cellular link to an AXYS website, which could be downloaded.

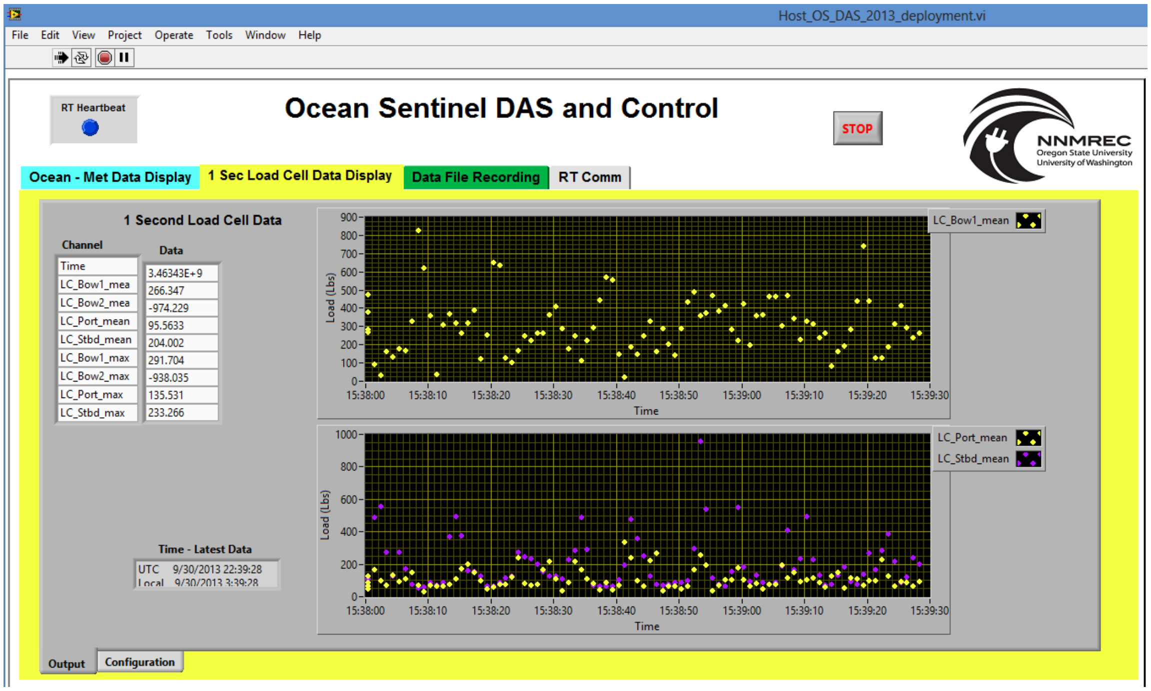


Figure 39: LabVIEW host user interface screen-shot

Load cell data were sampled by the CompaqRIO DAS at 20 Hz, and the files were saved in NI Technical Data Management Streaming (TDMS) format in three-hour blocks.

Environmental data were recorded in National Marine Electronics Association (NMEA) 0183 format. Wave, current, and other ocean data were continuously recorded by the TRIAXYS buoy and transmitted every 20 minutes to the Watchman 500 DAS. Air temperature, humidity, barometric pressure, and wind data were continuously recorded by the Watchman 500 DAS, and packaged into NMEA 0183 format every 10 minutes. Both sets of data were sent from the Watchman 500 DAS to the CompaqRIO DAS via serial link; however, only every other 10-minute Ocean Sentinel data file was recorded by the CompactRIO to be in sync with the 20-minute TRIAXYS data. Environmental data were combined into a single text file, which typically spanned an entire day. A sample text file is shown in Appendix H.1, and the NMEA format explanations are shown in Appendix H.2.

Pictures from the Ocean Sentinel's two cameras were transmitted to the AXYS data website every 10 minutes through the Watchman 500 DAS. These were readily available during the deployment.

Data from the AWAC were not available during the deployment.

4.2.2 Data Processing

Data were processed in MathWorks MATLAB and Microsoft Excel. Dr. Terry Lettenmaier provided various MATLAB scripts from the 2012 Ocean Sentinel deployment, which were used for data extraction from the NMEA and TDMS files. These scripts were edited and modified for use in this study. New scripts were also written for extracting and plotting load and environmental data.

4.2.2.1 NMEA Files

4.2.2.1.1 Data Extraction

The MATLAB script used in this study for extracting environmental data was based on Dr. Lettenmaier's original script, and utilized the NMEA message definitions shown in Appendix H.2. There were many lines of code added to and removed from this script to process additional data not used by Dr. Lettenmaier.

4.2.2.1.2 Error Correction

There were five NMEA text files that had various errors, most of which were in the spectral and current data. Each of these errors had to be repaired manually, and they are cataloged in Appendix I. The source of these errors is unknown, but could be a result of data corruption in the wireless link.

4.2.2.2 TDMS Files

4.2.2.2.1 Data Extraction

The MATLAB script used in this study for extracting the load cell data utilized a suite of MATLAB files written by James Hokanson for extracting data from TDMS files. The suite was version 2.5, which was last updated on 7/28/2012, and was publically available on the MathWorks website (MathWorks 2012). This file suite was used by Dr.

Lettenmaier for extracting power data from the WEC being tested in the 2012 Ocean Sentinel deployment. Dr. Lettenmaier's script was used as a starting point, and tailored for this study.

4.2.2.2.2 Error Correction

There were six TDMS files that would not properly load into MATLAB using the developed script. These files had only 1 sec of data, vice the normal 3 hr, so these files were imported into Excel using the TDM Importer add-in, which was downloaded from the National Instruments website (NI 2013-b). Empty structures were then created in MATLAB for the specific date/time, and the data was "cut and paste" from Excel.

These errors most likely occurred due to power cycling of the Ocean Sentinel, which was required to reboot the communication link if data were not transferring properly through the FTP.

4.3 Deployment

The main part of the 2013 Ocean Sentinel deployment was accomplished from July 24-29th 2013, and the AWAC was deployed on August 14th 2013. There were also many weeks of pre-deployment preparation.

The Ocean Sentinel had been in dry-dock at the Toledo Boat Yard since its 2012 summer deployment, so it needed various service-related checks, updates, and installations. The load cells needed to be integrated into the Ocean Sentinel mooring lines and CompactRIO DAS. The deployment vessels had to be booked, and all of the components had to be consolidated. The Ocean Sentinel and components were stored at three facilities: the Ocean Observatories Center (OOC), the Toledo Boat Yard, and the OSU Ship Operations Facility (Ship Ops). Ship Ops served as the final staging area for the deployment, so everything had to be transported there. Most of the components were transported via truck, but a tugboat was used to tow the Ocean Sentinel from the Toledo Boat Yard to Ship Ops. The R/V PACIFIC STORM was used to deploy the Ocean Sentinel and all related components at the test site, with the exception of the AWAC.

The AWAC was deployed using the R/V ELAKHA. All deployment days involved precise coordination of the deployment team, ship's crew, and Ship Ops staff.

4.3.1 Ocean Sentinel Refurbishment

AXYS Technologies sent a technician (George Puritch) to the Toledo Boat Yard to service the Ocean Sentinel from July 22-23, 2013. Mr. Puritch had a long task list, so not everything was completed in two days; however, he was able to complete all critical items. The main purpose of the trip was to complete functional checks on the Ocean Sentinel systems, inspect compartments for leaks and corrosion, and upgrade the firmware for various systems. Fuel was also delivered during this time for the diesel generator.

4.3.2 Facilities

4.3.2.1 Ocean Observatories Center

The Ocean Observatories Center (OOC) is located in south Corvallis, OR, and is part of the College of Earth, Ocean, and Atmospheric Sciences (CEOAS), OSU. It was purchased in 2011 as part of the Ocean Observatories Initiative (OOI) project, funded through the National Science Foundation (NSF). The OOC has a 12,500 ft^2 (1161 m^2) building with various laboratories, maintenance shops, and offices. The facility also has 40,000 ft^2 (3716 m^2) of outdoor storage and staging areas (Kearney 2011).

Figure 40: Ocean Observatories Center – OOC (Kearney 2010)

The OOC was the storage and staging area for many of the Ocean Sentinel system components between the 2012 and 2013 deployments. The majority of all mooring components were stored there, including anchors, lines, corner marker buoys, and connectors. The surface buoys were transported to the OOC from the Toledo Boat Yard to fabricate and attach new masts. Inventory and layout of all mooring components was done at the OOC prior to transport to Ship Ops.

4.3.2.2 Toledo Boat Yard

The Toledo Boat Yard is part of the Port of Toledo on the Yaquina River in Toledo, OR, and is capable of servicing boats up to 300 ton (273 tonne). It has a floating dry-dock for larger vessels, and a travel lift that can handle up to 90 ton (82 tonne) for getting boats in/out of the water (POT 2009). There is enough room in the yard for 20 boats on blocks, and 480 ft (146.3 m) of dock space for boats in the water. The Toledo Boat Yard can handle a variety of jobs, including sandblasting/painting, fiberglass hull repair, welding, and fabrication (Shoemake 2013).

The Ocean Sentinel was stored on blocks in the yard for approximately 10 months. During that time the Toledo Boat Yard applied a coat of red anti-biofouling paint below the waterline to the hull and yoke brackets, which was an effort to extend the service life of the buoy (Figure 41).

Figure 41: Ocean Sentinel in dry-dock at the Toledo Boat Yard (Hellin 2013-a)

The surface buoys were also serviced at the Toledo Boat Yard. Between deployments they were sandblasted and received a fresh coat of paint: black bio-fouling paint below the waterline and yellow high visibility paint above.

4.3.2.3 OSU Ship Ops

The Oregon State University Ship Operations Facility (Ship Ops) is located on Yaquina Bay adjacent to the Hatfield Marine Science Center (HMSC) in Newport, OR, and is home to two research vessels: R/V OCEANUS and R/V ELAKHA. The facility includes a wharf, a small craft moorage, three buildings, a locked storage yard, indoor and outdoor staging areas, three forklifts, and an 18 ton (16.4 tonne) mobile crane (see Figures 42 and 43). The facility's mission is "to support oceanographic and related research carried out by Oregon State University's Research Vessels… [as well as to] support the activities of CEOAS, HMSC and cooperating agencies, visiting research ships from other academic institutions or federal agencies, and others involved in related research activities" (Bailey 2013).

Figure 42: Overhead picture of Ship Ops (Bailey 2013)

Figure 43: Map of Ship Ops (Bailey 2013)

Both the R/V PACIFIC STORM and the R/V ELAKHA were loaded with equipment at Ship Ops. The mobile crane on the pier was used to load the anchors (Figure 44), while the crane onboard the R/V PACIFIC STORM was used to load most other equipment from the pier (Figure 45).

Figure 44: Anchor loading with Ship Ops crane (Hellin 2013-a)

Figure 45: Surface buoy load with onboard crane (Hellin 2013-a)

After being towed down the Yaquina River, the Ocean Sentinel was tied up at the small craft moorage behind R/V ELAKHA (Figure 46). Various in-water systems checks were performed here until the Ocean Sentinel was deployed on July 29th 2013.

Figure 46: Ocean Sentinel tied up at the Ship Ops small craft moorage (Hellin 2013-a)

4.3.3 Vessels

4.3.3.1 Wiggins Tug

Wiggins Tug and Barge is a private marine services company located in Yaquina Bay, OR, and provides tug and barge services to the Yaquina Bay and River system. The company has three tugs capable of up to 14,500 lb (64.6 kN) of bollard pull, three barges, and a skiff (Wiggins 2013). Wiggins was contracted to tow the Ocean Sentinel from the Toledo Boat Yard to Ship Ops (Figure 47), which is 10 miles (16.7 km).

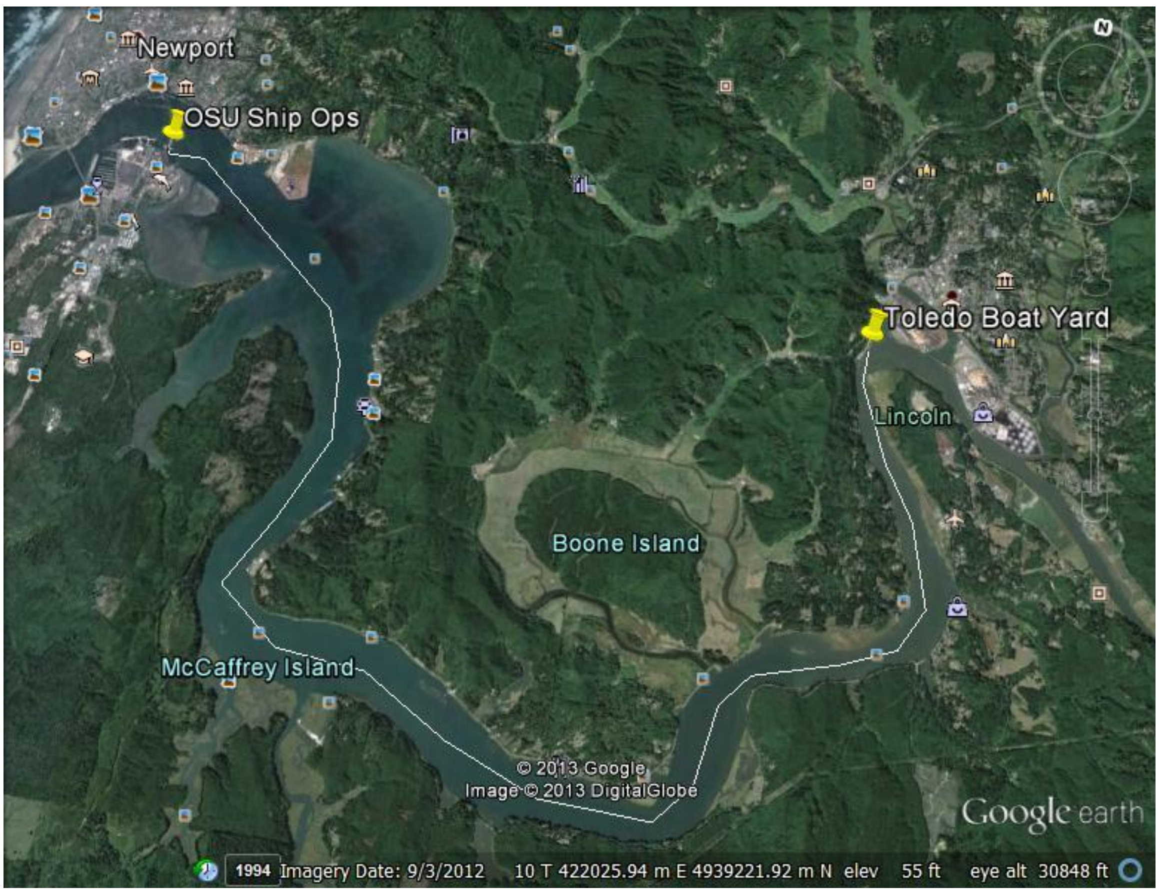


Figure 47: Map of Yaquina River tow (Google Earth)

4.3.3.2 R/V PACIFIC STORM

The R/V PACIFIC STORM is part of the Oregon State University Marine Mammal Institute (MMI), and is berthed at the Newport Harbor, Newport, OR. It conducts a variety of research deployments for OSU, including marine mammal surveys, seafloor mapping, and ROV (Remotely Operated Vehicles) deployments. The vessel is 84 ft (25.6 m) long, has a 5-ton (4.5 tonne) boom and a 5-ton (4.5 tonne) A-frame, and can accommodate up to seven people in addition to the crew. The aft deck area is 27 x 23 ft (8.2 x 7.0 m), and the stern is reinforced to accommodate heavy loads (OSU MMI 2013).

Figure 48: R/V PACIFIC STORM (OSU MMI 2013)

The R/V PACIFIC STORM was used for the 2012 and 2013 deployments of the Ocean Sentinel because of the vessel's availability, maneuverability, aft deck space, and lifting capacity, as well as the experience and involvement of the crew.

4.3.3.3 R/V ELAKHA

The R/V ELAKHA is part of OSU CEOAS, and is berthed at Ship Ops. The vessel is 54 ft (16.5 m) long with an aluminum hull, and is capable of carrying up to 8 people in addition to the crew. The R/V ELAKHA is intended for cruises less than 48 hours away from port, and has a range of 400 nm (741 km). The vessel has an A-frame capable of lifting 2 ton (1.8 tonne), and a 600 hp engine (OSU Ship Ops). The lifting capacity and aft deck space of the R/V PACIFIC STORM were not needed to deploy the AWAC, so the R/V ELAKHA was contracted because of the vessel's availability and cost, and the experience of the crew.

Figure 49: R/V ELAKHA (Fox 2013)

4.3.4 Transportation

4.3.4.1 Anchors, Surface Buoys, Lines, Connectors, Corner Marker Buoys

The anchors, lines, connectors, surface buoys, and corner marker buoys were all transported to Ship Ops by ScotCo Trucking, Philomath, OR on July 18th 2013 (Figure 50).

Figure 50: Mooring components being trucked from OOC to Ship Ops (Waldorf 2013)

4.3.4.2 Ocean Sentinel

To complete the tow from the Toledo Boat Yard to Ship Ops, Wiggins used the "Thea K" tug, which is 38 ft (17.3 m) long and has 425 hp (Figure 51). It took approximately 2 hr, and four people rode the Ocean Sentinel during the trip (Walt Waldorf, Chris Holm, Josh Baker, and Sean Moran). The tow had to coincide with high tide at the Toledo Boat Yard, because parts of the river are too shallow at low tide for the Ocean Sentinel.

Figure 51: Ocean Sentinel being towed by "Thea K" (Hellin 2013-a)

The yoke was secured in the "up" position during the tow to reduce the Ocean Sentinel's draft (Figure 52), and it was towed by a welded attachment point on the bow (Figure 53).

Figure 52: Yoke secured in the "up" position (Hellin 2013-a)

Figure 53: Ocean Sentinel tow point (Hellin 2013-a)

4.3.4.3 TRIAXYS

The TRIAXYS buoy was stored in the Wallace Energy Systems and Renewables Facility (WESRF), Dearborn Hall, OSU, after the 2012 deployment. It was transported to the Toledo Boat Yard on July 22nd 2013 for synchronization with the Ocean Sentinel, and transported to Ship Ops on July 24th 2013, both via pickup truck.

4.3.4.4 AWAC

The AWAC was stored and configured at the OOC, and it was transported to Ship Ops on August 14th 2013 via flatbed truck.

4.3.5 Methods

4.3.5.1 Anchor and Buoy Deployment

The R/V PACIFIC STORM was used for deploying all of the anchors and buoys from July 27-29th 2013. GPS Coordinates were given to the ship's captain (Ron "Yogi" Briggs), who navigated to the test site and approximate anchor locations. There is approximately 70 ft (21.3 m) between the R/V PACIFIC STORM pilot house, where the vessel GPS is located, and the stern of the boat, where the anchors were deployed. So once the vessel was close to the planned coordinates, a handheld Garmin GPSMAP 78 was used for final navigation and placement. The Garmin was held at the stern of the boat, and coordinates were called out to the team via handheld radio (see Figure 54).

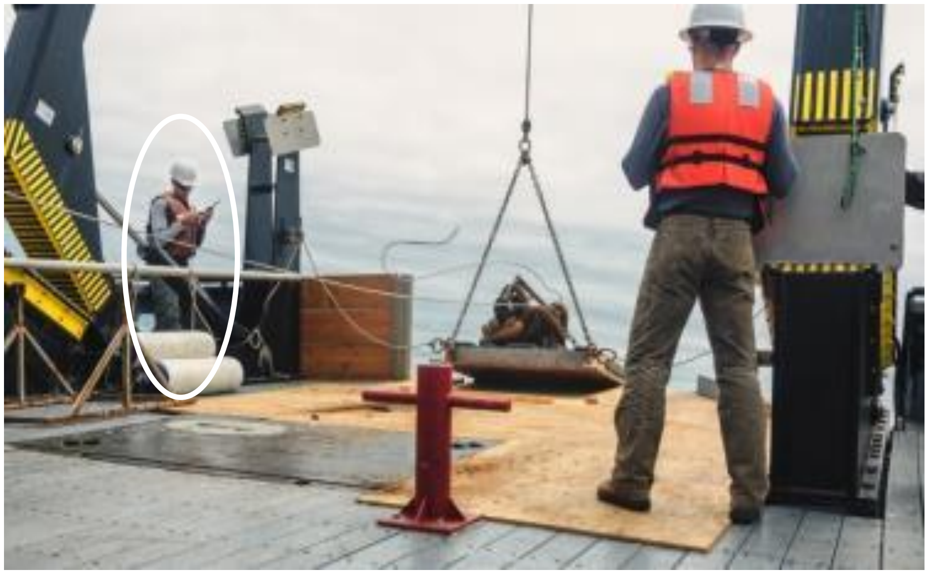


Figure 54: GPS Coordinates called from stern near the anchor drop point (Kight 2013)

The captain approached each anchor location motoring into the current, which was usually flowing from north-to-south. When the vessel was within 0.5 nm (0.9 km) of each location, the captain would slow down enough to just maintain forward progress against the current, while still retaining good vessel steerage (1 – 2 knots, 0.5 – 1 m/s). At this time the buoy would be deployed, and the mooring line would be fed out (see Figure 55). For the corner marker buoy and TRIAXYS mooring lines, this was a controlled pay out. For the Ocean Sentinel anchor chains it was a dynamic pay out. The buoy would then be dragged behind the vessel until reaching the anchor GPS location (see Figure 56). At this time the extra tie-downs on the anchors were removed.

Figure 55: Corner marker buoy deployed from R/V PACIFIC STORM (Kight 2013)

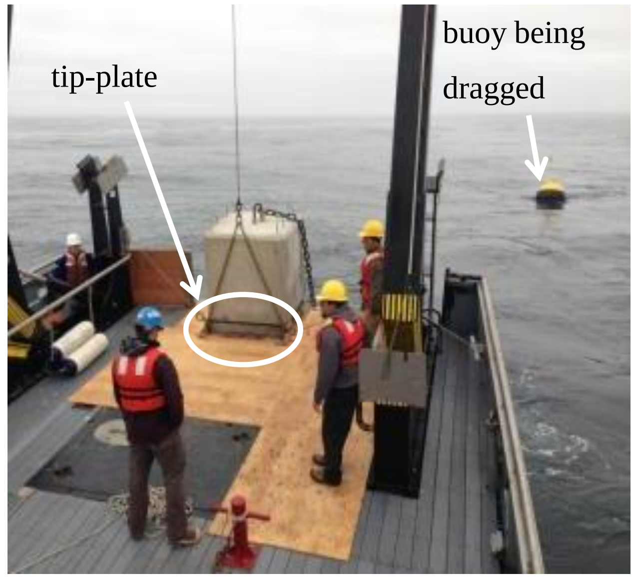


Figure 56: Ocean Sentinel anchor in position for placement (Kight 2013)

Each anchor was dropped off of the deck using a tip-plate (see Figure 56). This was a steel plate with a pallet on top that was fabricated for the 2012 deployment. It was bordered by the roller on the stern, and a wood frame on the other three sides. It had eyelets on the forward side that attach to the A-frame winch via two chains and a cable. When the anchor was ready to be dropped, the A-frame winch pulled up on the forward side of the tip-plate, causing the anchor to slide off.

Dropping each anchor in the proper location required precise coordination among the deployment team and ship's crew. The captain had to maintain a slow and steady speed as the vessel approached the location and the navigator (Josh Baker) had to keep everyone informed of the distance to the location. When the vessel was within 15 – 30 ft (4.6 – 9.1 m) of the GPS coordinate, the navigator would call "drop", and the crewman at the A-frame controls (Ken Serven) would activate the winch to pull up on the tip-plate. There was about a five second delay between the "drop" call and the anchor actually splashing the water. The timing of this process was very important, so a trial run was conducted for each Ocean Sentinel anchor before it was actually dropped. A trial run was not conducted for the other anchors since the precision of their placement was not critical.

The actual "dropped" GPS coordinates of each anchor was recorded when the anchor splashed the water. This was done using the "mark" command on the Garmin. This command had about a 1-second delay, which had to be taken into account.

4.3.5.2 Ocean Sentinel Deployment

The Ocean Sentinel was deployed on July 29th 2013 using the R/V PACIFIC STORM and its RHIB (Rigid-Hull Inflatable Boat). The Ocean Sentinel was towed behind the R/V PACIFIC STORM from Ship Ops to the test site, which was 10.5 miles (17 km) and took approximately 2 hours (Figure 57). During this transit Walt Waldorf rode on the Ocean Sentinel, Ken Serven drove the RHIB, and the rest of the team was on the R/V PACIFIC STORM (Figure 58).

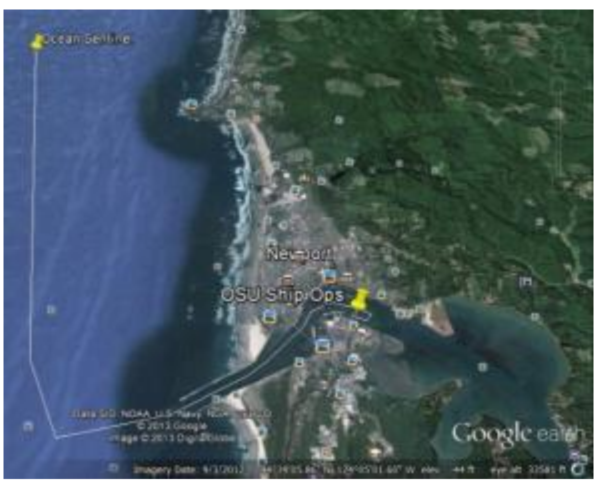


Figure 57: Ocean Sentinel test site tow map

Figure 58: Ocean Sentinel being towed behind R/V PACIFIC STORM (Kight 2013)

The R/V PACIFIC STORM towed the Ocean Sentinel to its approximate planned location within the test site, and released it from the tow line. At this time three members of the deployment team (Sean Moran, Josh Baker, and Chris Holm) joined Ken Serven on the RHIB to assist with connecting the Ocean Sentinel to its anchors.

The Ocean Sentinel was connected to the bow anchor first. The bow anchor mooring line was pre-connected to the yoke in dry-dock, and stowed onboard the Ocean Sentinel. The first step was to transfer this line from the Ocean Sentinel to the RHIB. Small flotation buoys were attached to the end of the mooring line so it would not sink if dropped. The RHIB then motored to the bow surface buoy, paying out the mooring line as it progressed. The last step was to connect the mooring line to the surface buoy (see Figure 59). The team disconnected the spectra line from the top of the buoy, and connected it to the Bow Anchor mooring line with two shackles. The motions of the RHIB and the surface buoy, the weight of the shackles, and the size and stiffness of the cotter pins all made this challenging.

Figure 59: The team making the Bow Anchor connection (Kight 2013)

Next the Ocean Sentinel was connected to the port anchor. The port anchor mooring line was stowed onboard the R/V PACIFIC STORM, and had to be transferred to the RHIB (see Figure 60). Once this was complete, the RHIB motored to the port surface buoy and attached one end of the mooring line to it using the same method described for the bow anchor. The RHIB then motored toward the Ocean Sentinel, paying out the mooring line until reaching its end. Since there was still a gap between the RHIB and the Ocean

Sentinel, the team attached a pull-line to the end of the mooring line, and continued on to the Ocean Sentinel. The pull-line was subsequently fed through a snatch-block (pulley) attached to the strength-termination frame on the stern of the Ocean Sentinel (see Figure 61). The pull-line was then attached to a cleat on the RHIB, and the RHIB motored away until the end of the mooring line reached the Ocean Sentinel. This moved the Ocean Sentinel and port surface buoy closer together, and put tension in the port anchor mooring line. Once the end of the mooring line reached the Ocean Sentinel it was temporarily tied off using friction knots, and connected to the swivel using two shackles. The motions of the Ocean Sentinel, location of the swivel, and size of the cotter pins all made this connection challenging.

Figure 60: Mooring line in the RHIB (Kight 2013)

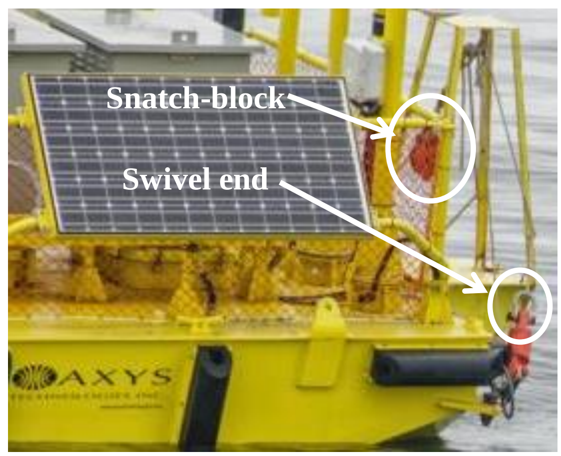


Figure 61: Anchor mooring line pulley assembly on the Ocean Sentinel (Kight 2013)

The Ocean Sentinel was connected to the starboard anchor last using the same method described for the port anchor. Since this was the final connection, the RHIB had to pull harder on the pull-line to get the Ocean Sentinel and starboard surface buoy in place. The main forces opposing this connection were the current and the other two mooring lines.

4.3.5.3 AWAC Deployment

The AWAC was deployed on August 14th 2013 using the R/V ELAKHA. It was deployed separately because it was a late addition to the deployment plan and was not ready by the end of July. The R/V ELAKHA was capable of deploying the AWAC, and could accommodate the later deployment schedule. In addition to the ship's crew, Walt Waldorf, Dr. Ean Amon, Josh Baker, and Malachi Bunn were part of this deployment team.

The AWAC was loaded onboard the R/V ELAKHA using the crane at Ship Ops (Figure 62). GPS Coordinates were then given to the ship's captain (Mike Kriz), who navigated to the test site and AWAC location. Once at the proper location, the vessel was held in place while the AWAC was lowered into the water. When the AWAC landed on the seabed, the lowering line was released (Figure 63) and pulled back to the surface.

Figure 62: AWAC being loaded on R/V ELAKHA with Ship Ops Crane

Figure 63: AWAC rigged for deployment

After the AWAC deployment was complete, the vessel motored to the Ocean Sentinel and three team members (Walt Waldorf, Dr. Amon, and Malachi Bunn) boarded it to attach a corrosion experiment to the hull. This device was about the size of a briefcase, and was attached to the railings with heavy-duty zip-ties.

4.4 Recovery

The 2013 Ocean Sentinel recovery took place from October 3 – 4th 2013. The corner marker buoys and the AWAC were recovered on October 3rd, and the TRIAXYS and Ocean Sentinel on October 4th. The anchors and surface buoys were left at the deployment site for the winter. The R/V PACIFIC STORM and its RHIB were used for recovery operations, and all components were offloaded at Ship Ops. The corner marker buoys, TRIAXYS, and AWAC, as well as all of the mooring lines and anchors for these components, were transported to the OOC. The Ocean Sentinel was docked at Ship Ops until October 17th, when it was towed to the Toledo Boat Yard.

4.4.1 Methods

4.4.1.1 Corner Marker Buoys

The corner marker buoys were the first components recovered, to make room at the site for recovering all of the other components. The R/V PACIFIC STORM slowly came alongside each corner marker buoy, which was hooked using a long pole with a large releasable hook and a line (Figure 64). The line was then attached to the R/V PACIFIC STORM's boom, and the buoy was lifted out of the water and onto the deck (Figure 65). The corner marker buoy mooring line was then transferred to the R/V PACIFIC STORM's winch, and the line was reeled in until reaching the anchor. The anchor load was then transferred to the boom, which lifted the anchor over the roller and onto the deck.

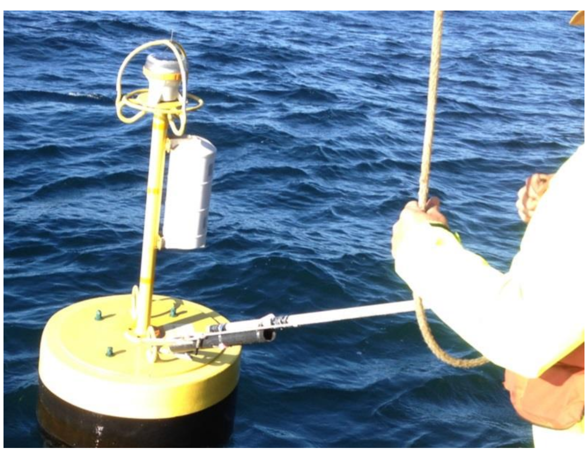


Figure 64: Corner marker buoy being retrieved with releasable hook

Figure 65: Corner marker buoy being lifted by boom

4.4.1.2 AWAC

The AWAC was the last component recovered on October 3rd 2013. Two surface floats were attached to the AWAC with synthetic line and steel chain, approximately 246 ft (75 m) from its bottom location. The R/V PACIFIC STORM slowly came alongside the surface floats, and they were hooked using a long pole with a large releasable hook and a line. The line was attached to the winch, which reeled it in until reaching the floats. The load was transferred to the boom, which lifted the floats over the roller and onto the deck. The load was then transferred back to the winch, which reeled in the float line until reaching the AWAC. The boom hook was then attached to the center lifting eye on the AWAC, and both the boom and the winch were used to lift it onto the deck (Figure 66).

Figure 66: AWAC recovered on deck

4.4.1.3 TRIAXYS

The TRIAXYS was the first component recovered on October 4th 2013. The RHIB motored to the buoy with five personnel (Ken Serven, Tully Rohrer, Josh Baker, Walt Waldorf, and Kevin Buch). The TRIAXYS was first lassoed with synthetic line to keep the RHIB next to it. Walt Waldorf and Kevin Buch then conducted a dive operation on the TRIAXYS using SCUBA gear. They attached a synthetic lifting line to the TRIAXYS mooring chain (located below the bungee line), which was approximately 40 ft (12 m) deep, and the other end was attached to surface floats. The team members onboard the RHIB then attached a second lifting line directly to the TRIAXYS (Figure 67). Once the operation was complete, the team motored back to the R/V PACIFIC STORM.

The R/V PACIFIC STORM then slowly came alongside the TRIAXYS, and it was hooked using a long pole with a large releasable hook and a line. The line was attached to the boom, and the TRIAXYS was lifted out of the water and onto the deck (Figure 68). The surface floats attached to the other lifting line were then hooked, and the line was transferred to the winch. The winch reeled in the mooring chain until reaching the anchor. The anchor load was then transferred to the boom, which lifted the anchor over the roller and onto the deck.

Figure 67: Recovery team attaching second lifting line to TRIAXYS (Hellin 2013-b)

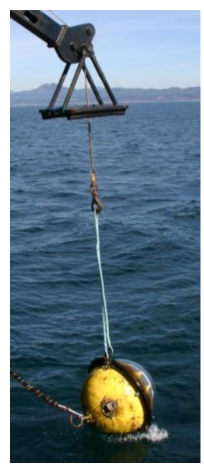


Figure 68: TRIAXYS lifted by boom (Hellin 2013-b)

4.4.1.4 Ocean Sentinel

The Ocean Sentinel was the last component recovered on October 4th 2013, and was the longest operation. The RHIB motored to the Ocean Sentinel with six personnel (Ken Serven, Tully Rohrer, Josh Baker, Walt Waldorf, Sean Moran, and Dr. Ean Amon). Josh, Sean, and Ean were transferred to the Ocean Sentinel, while Ken, Walt, and Tully motored to the port surface float. The spectra line below the surface float was recovered using a grappling hook (Figure 69). The spectra line was then cut, and a surface float was attached to the other end of the port mooring line. The RHIB then carried the surface float to the Ocean Sentinel. The surface float and mooring line were hauled onboard the Ocean Sentinel, and the other end of the mooring line was left connected to the load cell and swivel. The load cell and swivel were tied to the bend connector to secure them out of the water (Figure 70).

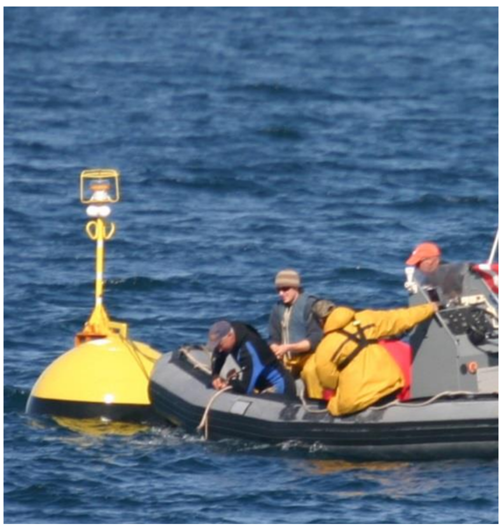


Figure 69: Spectra line being recovered with grappling hook (Hellin 2013-b)

Figure 70: Load cells and swivels tied to bend restrictor (Hellin 2013-b)

The RHIB then motored to the starboard surface float, but the spectra line could not be recovered with the grappling hook because there was too much tension in the line. Kevin and Walt had to conduct a dive operation and cut the spectra line underwater. The starboard mooring line was then recovered using the same method as the port mooring line.

The bow mooring line was the last to be disconnected. The RHIB motored to it, but the spectra line could not be recovered with the grappling hook because there was too much tension in the line. The dive team also could not conduct a dive operation because the current had picked up and would move them out of position too quickly. The team then decided to use the RHIB to tow the Ocean Sentinel closer to the bow surface buoy and relieve tension in the bow mooring line. Once half the distance was taken up, the tow line was tied to the top of the surface buoy. The team was then able to recover the spectra line with the grappling hook, and the mooring line was recovered using the same method as the port and starboard lines. When the team onboard the Ocean Sentinel reached the end of mooring line, it was secured to a cleat on the deck of the Ocean Sentinel.

The Ocean Sentinel was then tied to the RHIB, which towed it to the R/V PACIFIC STORM, where it was tied to the port side of the ship. First, the boom was used to lift the rest of the bow mooring line and the most of the yoke chain out of the water. The yoke was also lifted to a more horizontal position to reduce the Ocean Sentinel draft for towing it into Newport Harbor. The yoke chain was secured to a cleat on the Ocean Sentinel deck. Second, personnel onboard the RHIB attached the tow line to the tow eye on the bow of the Ocean Sentinel, which was also attached to cleats on the stern of the R/V PACIFIC STORM. The Ocean Sentinel was then untied from the port side of the R/V PACIFIC STORM, and allowed to drift behind the ship to its final tow position (Figure 71). Afternoon winds and large relative motions of all three vessels made these tasks challenging.

Figure 71: Ocean Sentinel being towed behind R/V PACIFIC STORM (Hellin 2013-b)

The Ocean Sentinel was towed to Ship Ops, where it was tied up to the small craft moorage. The RHIB was used for final towing and maneuvering once at Ship Ops. The TRIAXYS, its anchor, and all gear were offloaded at Ship Ops using the boom on the R/V PACIFIC STORM.

4.4.2 Transportation, Cleaning, and Storage

The corner marker buoys, TRIAXYS, AWAC, mooring lines and anchors for these components, as well as most of the gear, were transported to the OOC with a flatbed truck. The corner marker buoys, mooring lines and anchors were stored outdoors, and the AWAC and TRIAXYS were stored in one of the bays at the OOC. The TRIAXYS and AWAC were later transported to WESRF via pickup truck.

The Ocean Sentinel was docked at Ship Ops until October 17 2013, when it was picked up by Wiggins and towed to the Toledo Boat Yard. Once there it was lifted out of the water and pressured washed. The Ocean Sentinel was then set on blocks in the yard.

Table 7: Field Observation Task List

Task	Start	Finish	Location	Assets	Personnel
Predeployment					
Order Load Cells	6/12/2013	6/12/2013	-	-	Josh Baker
Book R/V PACIFIC STORM	6/19/2013	6/19/2013	-	-	Walt Waldorf
Update Permits	6/19/2013	6/19/2013	-	-	Sean Moran
Inventory Gear	6/20/2013	6/20/2013	OOC	-	Walt Waldorf, Chris Holm, Ricky Verlini
Surface Buoy Mast (Design, Paint, Manufacture, Integrate)	6/20/2013	7/15/2013	OOC, Toledo Boat Yard	-	Walt Waldorf, Chris Holm, Toledo Boat Yard Personnel
Reprogram CompaqRIO	6/21/2013	7/16/2013	-	-	Dr. Terry Lettenmaier, Dr. Ean Amon
Order Load Cell Cables	6/21/2013	6/21/2013	-	-	Dr. Ean Amon
Order Load Cell Swivels and Shackles	6/21/2013	6/21/2013	-	-	Walt Waldorf
Order Load Cell Conduit	6/24/2013	6/24/2013	-	-	Dr. Ean Amon
Book Wiggins Tug	7/2/2013	7/2/2013	-	-	Josh Baker
Prep TRIAXYS	7/15/2013	7/24/2013	WESRF	-	Dr. Ean Amon
Ocean Sentinel Systems Checks	7/17/2013	7/25/2013	Toledo Boat Yard, Ship Ops	-	Dr. Ean Amon, Dr. Terry Lettenmaier
Load Cell Integration/Calibration	7/18/2013	7/24/2013	Toledo Boat Yard	-	Dr. Ean Amon, Josh Baker, Dr. Terry Lettenmaier
Transport Anchors, Surface Buoys, Mooring Lines, Connectors, Corner Marker Buoys	7/19/2013	7/19/2013	OOC - Ship Ops	Commercial Truck	Walt Waldorf, ScotCo Trucking
Ocean Sentinel Refurbishment	7/22/2013	7/23/2013	Toledo Boat Yard	-	George Puritch (AXYS), Dr. Ean Amon
Transport TRIAXYS	7/22/2013	7/24/2013	WESRF - Toledo Boat Yard - Ship Ops	Pickup Truck	Dr. Ean Amon
Tow Ocean Sentinel	7/24/2013	7/24/2013	Toledo Boat Yard - Ship Ops	Wiggins Tug	Walt Waldorf, Chris Holm, Josh Baker, Sean Moran, Dr. Ean Amon, Dan Hellin, Toledo Boat Yard Personnel, Grant Snyder (Wiggins)
Load 1st Anchor and 2 Corner marker buoys	7/24/2013	7/24/2013	Ship Ops	R/V PACIFIC STORM	Walt Waldorf, Chris Holm, Ricky Verlini, Sean Moran, Dan Hellin, Ship Ops Personnel, R/V PACIFIC STORM crew (Yogi Briggs, Ken Serven, Jeff Lawrence)
Assemble/Prep AWAC	7/31/2013	8/14/2013	OOC	-	Walt Waldorf, Dr. Ean Amon
Transport AWAC	8/14/2013	8/14/2013	OOC - Ship Ops	Flatbed Truck	Walt Waldorf
Deployment					
Deploy Anchors and Corner marker buoys. Load for next day.	7/25/2013	7/27/2013	Ship Ops - Test Site	R/V PACIFIC STORM	Walt Waldorf, Chris Holm, Ricky Verlini, Josh Baker, Sean Moran, Dr. Ean Amon, Ship Ops Personnel, R/V PACIFIC STORM crew (Yogi Briggs, Ken Serven, Jeff Lawrence)
Deploy Ocean Sentinel and TRIAXYS	7/29/2013	7/29/2013	Ship Ops - Test Site	R/V PACIFIC STORM, RHIB	Walt Waldorf, Chris Holm, Josh Baker, Sean Moran, Dr. Ean Amon, R/V PACIFIC STORM crew (Yogi Briggs, Ken Serven, Jeff Lawrence), Pat Kight
Deploy AWAC	8/14/2013	8/14/2013	Ship Ops - Test Site	R/V ELAKHA	Walt Waldorf, Josh Baker, Dr. Ean Amon, R/V ELAKHA crew, Malachi Bunn
Recovery					
Recover AWAC and Corner marker buoys	10/3/2013	10/3/2013	Test Site - Ship Ops	R/V PACIFIC STORM	Walt Waldorf, Tully Rohrer, Josh Baker, Sean Moran, Dr. Ean Amon, R/V PACIFIC STORM crew (Yogi Briggs, Ken Serven, Jeff Lawrence), Jason Kiel
Transport AWAC and Corner marker buoys	10/3/2013	10/3/2013	Ship Ops - OOC	Flatbed Truck	Walt Waldorf, Chris Holm
Recover Ocean Sentinel and TRIAXYS	10/4/2013	10/4/2013	Test Site - Ship Ops	R/V PACIFIC STORM, RHIB, SCUBA Gear	Walt Waldorf, Tully Rohrer, Josh Baker, Sean Moran, Dr. Ean Amon, R/V PACIFIC STORM crew (Yogi Briggs, Ken Serven, Jeff Lawrence), Kevin Buch, Dan Hellin, Nancy Steinberg, Brett Bosma, Brendan Cahill
Transport TRIAXYS and gear	10/4/2013	10/4/2013	Ship Ops - OOC	Flatbed Truck	Walt Waldorf, Chris Holm
Tow Ocean Sentinel	10/17/2013	10/17/2013	Ship Ops - Toledo Boat Yard	Wiggins Tug	Sean Moran, Dr. Ean Amon, Toledo Boat Yard Personnel, Grant Snyder (Wiggins)

5 Numerical Model

5.1 Original Model

The starting point for the numerical model used in this study was the Ocean Sentinel mooring system model built in OrcaFlex by Carl Barrett of 3U Technologies. The model included the Ocean Sentinel buoy, the yoke, the surface buoys, all of the mooring lines and chains, and the sinker weight attached to the bow mooring chain.

The Ocean Sentinel was modeled using a Vessel with displacement and load Response Amplitude Operators (RAO), as well as stiffness, added mass, and damping matrices (for specifics on OrcaFlex theory, see Appendix J). A "mass correction clump" weighing 1,470 lb (668 kg) was also attached to it, approximately 24 ft (7.3 m) above the deck. This mass correction clump corrected for the difference between the as-shipped weight/center-of-gravity of the Ocean Sentinel, and the values used to calculate the RAO's. The mass correction clump was modeled using a 6D Buoy. The yoke was modeled using a 6D Buoy, and the yoke pivot pins were modeled using Lines. A customized drawing was also produced to accurately display the Ocean Sentinel. No changes were made to the Ocean Sentinel, mass correction clump, or yoke models.

The surface buoys were modeled using 3D Buoys, and no changes were made to these objects.

The mooring lines and chains were modeled using Lines, and the sinker weight was modeled as a 500 lb (227 kg) clump-weight attached to the bow mooring chain. Changes were made to the properties, lengths, and locations of all of these objects.

The anchors were not built into the original model. All of the mooring chains were anchored directly to the seabed, which was not changed.

The seabed was modeled flat with a depth of 154 ft (47 m) using the linear seabed theory with default values. No changes were made to the seabed since the depth was correct, and none of the mooring components in the field observation significantly penetrated the seabed.

5.2 Modifications

Changes were made to the original model to accurately represent the 2012 and 2013 deployed configurations, and improve simulation results for tension forces. These changes were made with input from Carl Barrett, Sean Moran, and many of the documents detailing the 2012 deployment.

5.2.1 2012 Model

The following changes were made so the model would accurately represent the 2012 deployed configuration.

- Anchored positions of the three mooring chains were changed to reflect the actual deployed 2012 GPS coordinates, and raised from 0.5 ft (0.15 m) to 3.5 ft (1.1 m) above the seabed to accurately represent the anchor connection points.
- The port and starboard mooring chains were increased from 177 ft (54 m) to 183 ft (55.8 m).
- The bow mooring chain was decreased from 341.2 ft (104 m) to 272.3 ft (83 m), and the 500 lb (227 kg) clump-weight was removed.
- The properties of the last 13 ft (4 m) of each mooring line connected to the surface buoy were changed from synthetic line to chain.
- The properties of the last 33 ft (10 m) of the bow mooring line connected to the yoke were changed from synthetic line to chain.
- The outer diameter of the synthetic line was changed from 0.125 ft (0.038 m) to 0.101 ft (0.031 m), and the axial stiffness was changed from 400 kips (90 kN) to 356 kips (80 kN). These changes were made to properly represent the synthetic mooring lines, based on the OrcaFlex method for calculating these values (see Appendix A.3 for calculation).

The following changes were made to more accurately represent objects in OrcaFlex, and improve simulations results.

- The bending stiffness was set to zero for all lines. Chain and synthetic rope both have a very low bending stiffness, and are best modeled in OrcaFlex by setting this value equal to zero.
- The number of segments was increased to every 2 ft (0.6 m) on the main parts of all Lines (except for the yoke pins), and every 1 ft (0.3 m) on all of the ends. This gave improved simulation results, especially near the connection points. Segmentation was not increased to 1 ft (0.3 m) for the main part of the Lines because this added a great deal of computation time without improved simulation results.

5.2.2 2013 Model

The following changes were made to the model to accurately represent the 2013 deployed configuration.

- The anchored positions of the three mooring chains were changed to reflect the actual deployed 2013 GPS coordinates.
- The properties of the last 13 ft (4 m) of each mooring line connected to the surface buoy were changed from chain to spectra line.
- Spectra line was added as a Line type with properties representing 1" (2.5 cm) Samson AmSteel. Outer diameter and axial stiffness were calculated based on the OrcaFlex method (see Appendix A.3 for calculation).

5.3 Simulations

5.3.1 Model Development

During the model development phase shorter simulation times were used with Dean Stream regular waves, a constant surface current, and constant wind. Full Statics, including vessels and buoys, was used prior to the dynamic simulations. Implicit integration was used with a time-step of 0.0005 sec for most of the simulations, because the model would not converge with larger time steps. These simulations were primarily used for testing model changes and improvements, and generally tool 1 – 2 hr.

5.3.2 Model Comparison with Field Data

For all of the model comparison simulations, 20-min simulation times were used to align with the 20-min environmental data given by the TRIAXYS. Full Statics, including vessels and buoys, was used prior to the dynamic simulations. Implicit integration was used with a time-step of 0.0005 sec, because the model would not converge with larger time steps.

User-defined wave spectra with multi-directional spreading were used. The spectral energies and frequencies were directly input from TRIAXYS data. The directional spectra were created using ten wave directions and a spreading exponent of thirty, to approximate the average directional spread given by the TRIAXYS. A current-depth profile was used, which was input from TRIAXYS ADCP data. Linear interpolations were used from the top of the ADCP data to the sea-surface and from the bottom of the data to the seabed. Constant wind and direction were used, which were input from the TRIAXYS data.

The number of segments on all of the mooring chains was decreased to every 8 ft (2.44 m) for the main part of the chains to decrease simulation times. This was considered reasonable because chain tensions were not being directly compared to field data. Despite this change, simulations still took 3 – 4 days to complete.

6 Field Observation Results

6.1 Data

Data from 7/30/2013 – 10/03/2013 were used for the analysis in this study. All data files were recorded in Coordinated Universal Time format (UTC).

All average and maximum values for the bow line load cells have been taken from 7/30/2013 – 9/29/2013 because both bow line load cells failed on 9/30/2013 (discussed in further detail in Section 6.4.2).

6.2 Environmental Conditions

Environmental conditions during most of the deployment were typical for summers at the NETS (see Section 3.3). Values for significant wave height, significant wave period, dominant wave direction, surface current, and wind are shown in Figures 72 – 77, and average values for the deployment were:

- H_s = 5.27 ft (1.61 m)
- T_s = 8.27 s
- Dominant Wave Direction = 269° (from this direction)
- Surface Current = 0.50 knots (0.26 m/s), generally toward North or South
- Wind = 8.43 knots (4.33 m/s), generally from North or South

Toward the end of the deployment a number of storms and swells came through the area that brought unique conditions. The largest seas, currents, and wind gusts occurred during this time. Maximum values for maximum wave height and period, surface current velocity, and wind gust velocity were:

- H_{max} = 39.19 ft (11.94 m) at T_{max} = 11.92 s, from 261°
- Surface Current = 1.96 knots (1.01 m/s), to 357°
- Wind Gust = 53.46 knots (27.50 m/s), from 179°

6.2.1 Wave Data

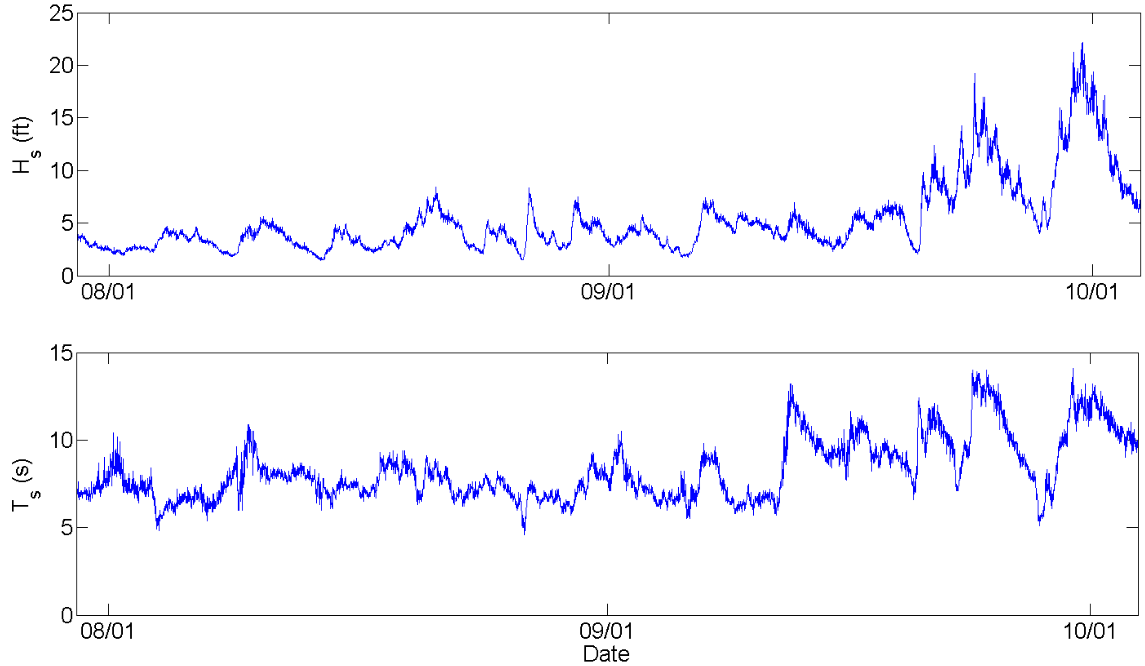


Figure 72: Significant wave height and period for 2013 deployment

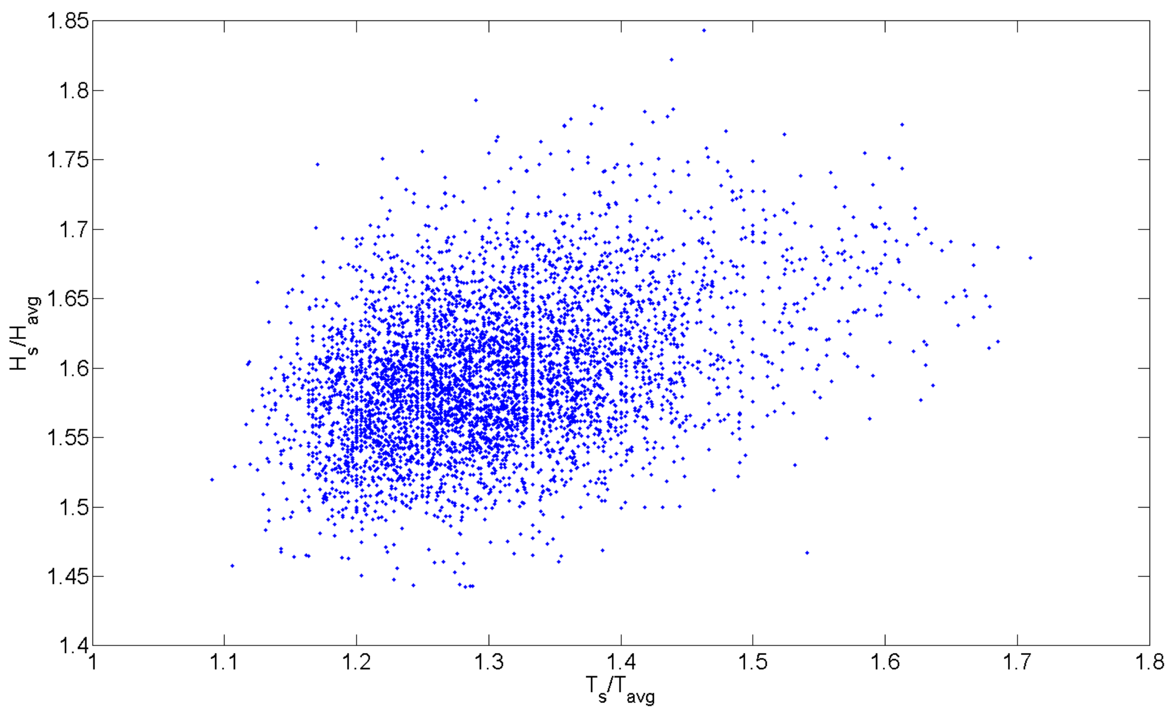


Figure 73: Joint Distribution for 2013 deployment

6.2.2 Current and Wind Data

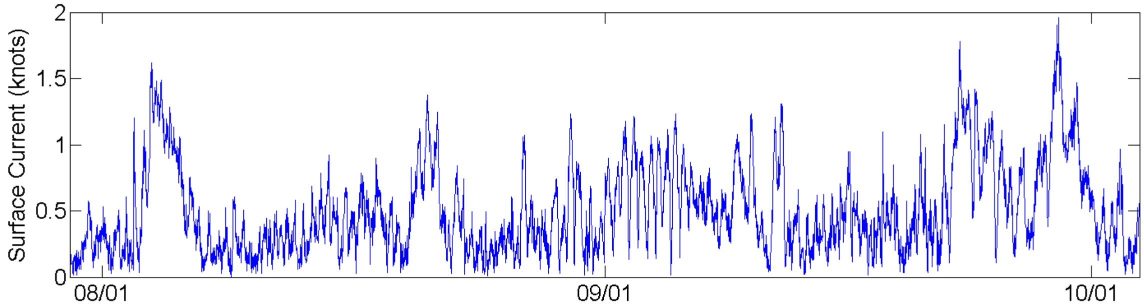


Figure 74: Surface current velocity for 2013 deployment

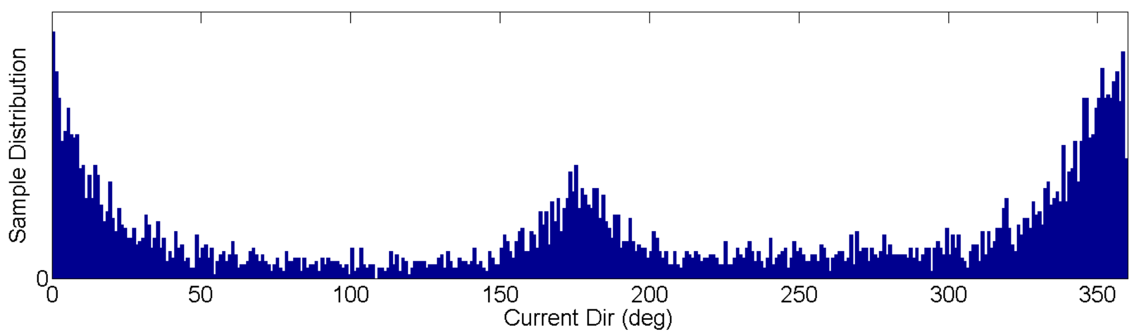


Figure 75: Surface current direction (flowing to) distribution for 2013 deployment

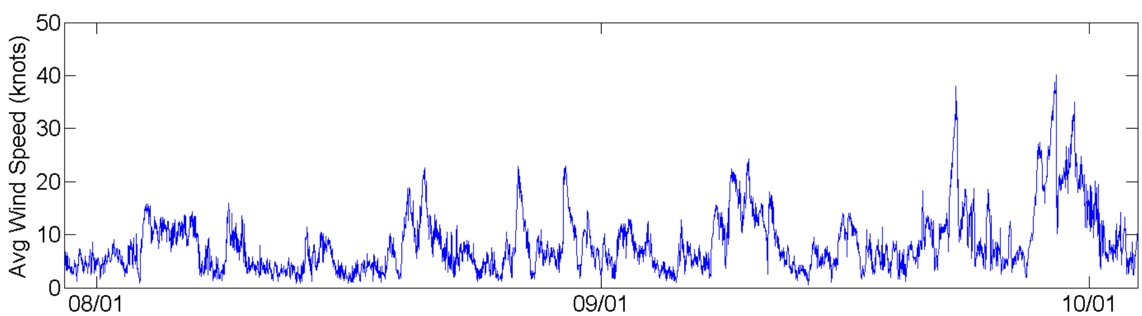


Figure 76: Average wind speed for 2013 deployment

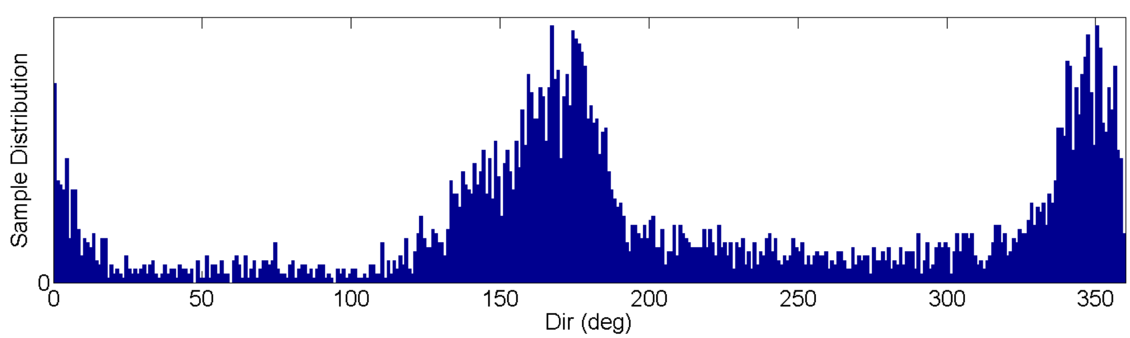


Figure 77: Wind direction (coming from) distribution for 2013 deployment

6.3 Mooring Line Tension

6.3.1 Mean Loads

The three-hour average tension in each mooring line is shown in Figure 78, and the averages for the deployment are listed below.

- Bow line load cell #1 = 389.66 lb (1.73 kN)
- Bow line load cell #2 = 360.00 lb (1.60 kN)
- Port line = 195.01 lb (0.87 kN)
- Starboard (Stbd) line = 161.01 lb (0.72 kN)

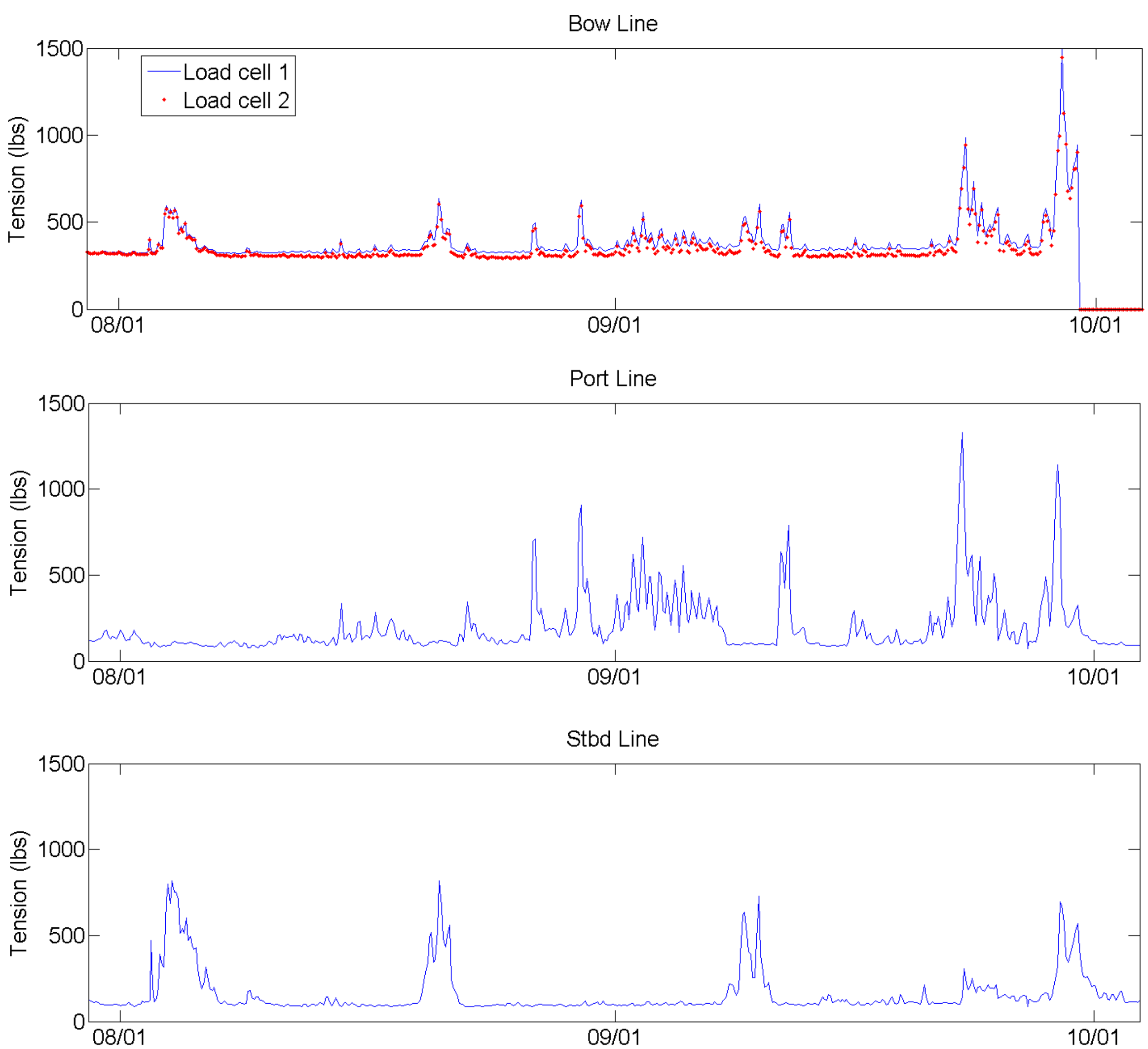


Figure 78: Three-hour average mooring line loads during the deployment

6.3.2 Max Loads

The three-hour maximum tension in each mooring line is shown in Figure 79 and the maximum values for the deployment are listed below. Figure 80 shows three-hour maximum tensions in comparison with H_{max} and surface current velocity.

- Bow line load cell #1 = 7832.91 lb (34.84 kN)
- Bow line load cell #2 = 7788.87 lb (34.64 kN)
- Port line = 7999.83 lb (35.58 kN)
- Starboard (Stbd) line = 3041.32 lb (13.53 kN)

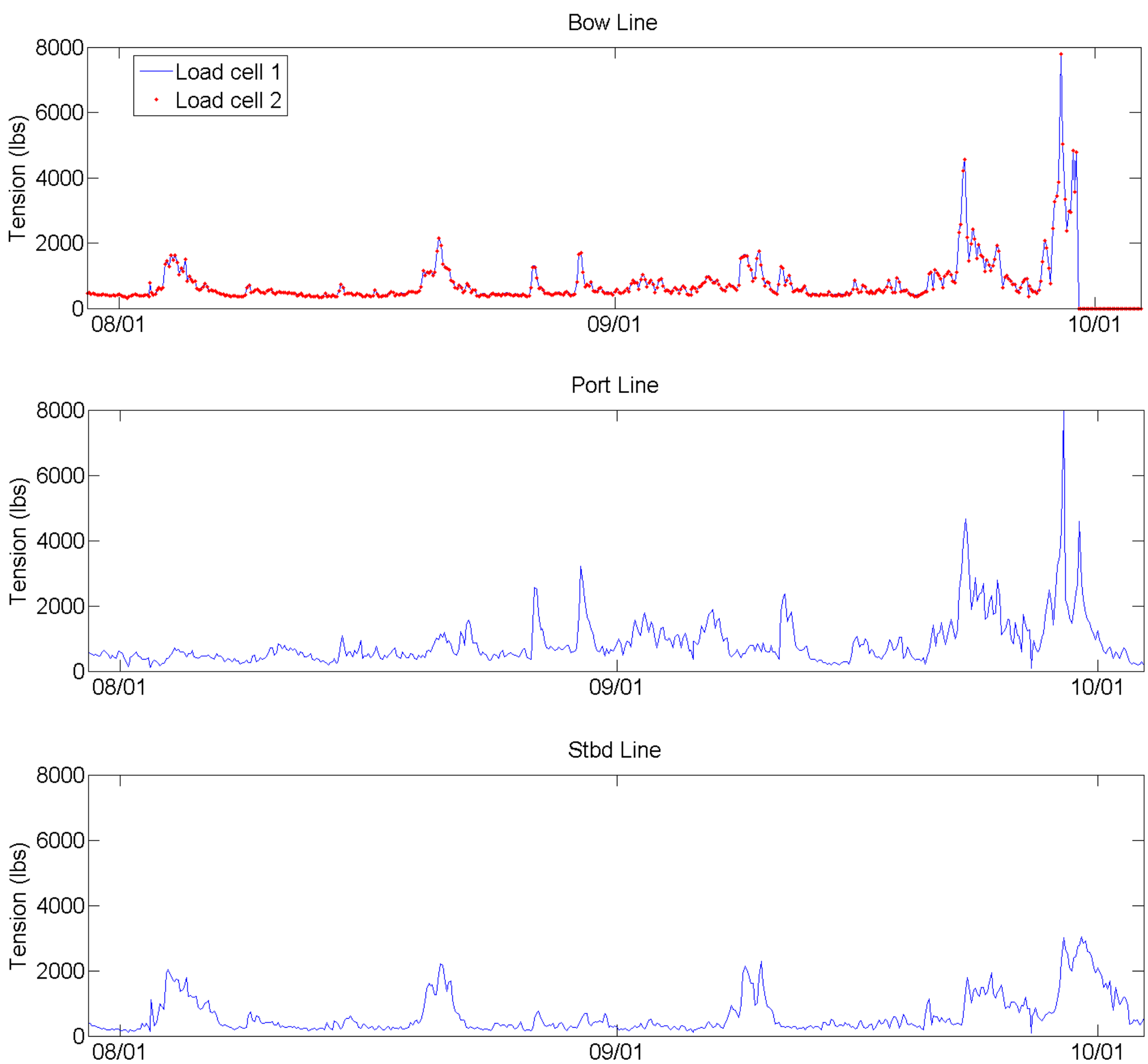


Figure 79: Three-hour maximum mooring line loads during the deployment

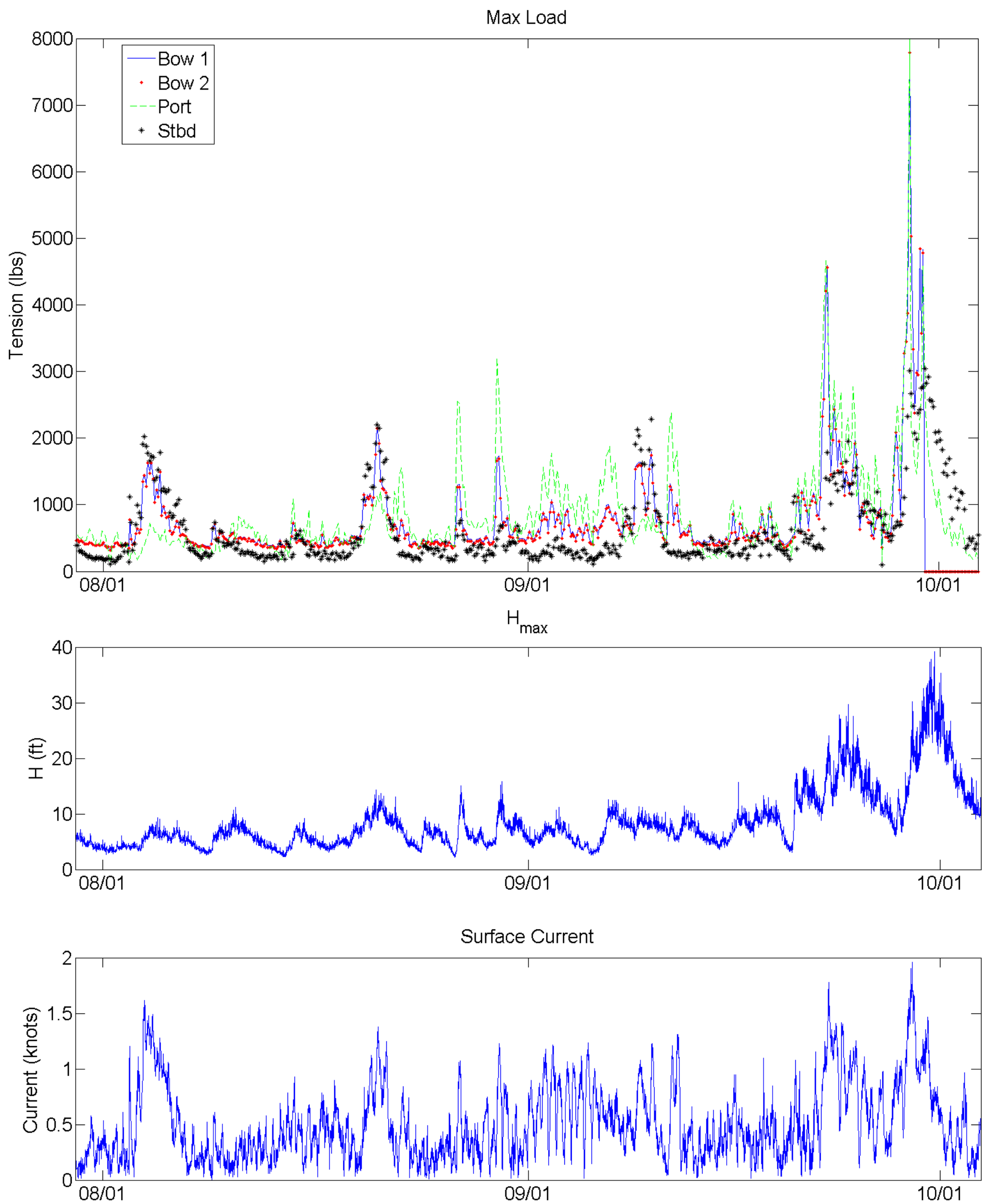


Figure 80: Max mooring line loads, H_{max}, and Surface Current during the deployment

6.4 Notable Events

6.4.1 Anchor Movement

On 9/22/2013 the Ocean Sentinel strayed out of its watch circle and established a new mean position approximately 460 ft (140.2 m) to the North, and most likely dragged its anchors. The new anchor positions were measured via the anchor surface floats during recovery operations. The new bow anchor position was within its original watch circle, so it likely did not move. The starboard anchor was measured 120 ft (36.6 m) to the Southwest of its original position, which was outside of its original watch circle by 27 ft (8.2 m). However, given the direction of movement in comparison to the Ocean Sentinel, and the uncertainty of the original anchor position measurement (discussed in Section 7.6), the starboard anchor most likely did not move. The port anchor was measured approximately 430 ft (131 m) to the Northwest of its original position, which is well outside of its watch circle radius of 93 ft (28.3 m) and uncertainties in the original anchor position measurement. Therefore, the Ocean Sentinel most likely dragged just its port anchor, which is shown in Figure 81. Mooring line loads during this event are shown in comparison with simulation results in Section 7.3.2.

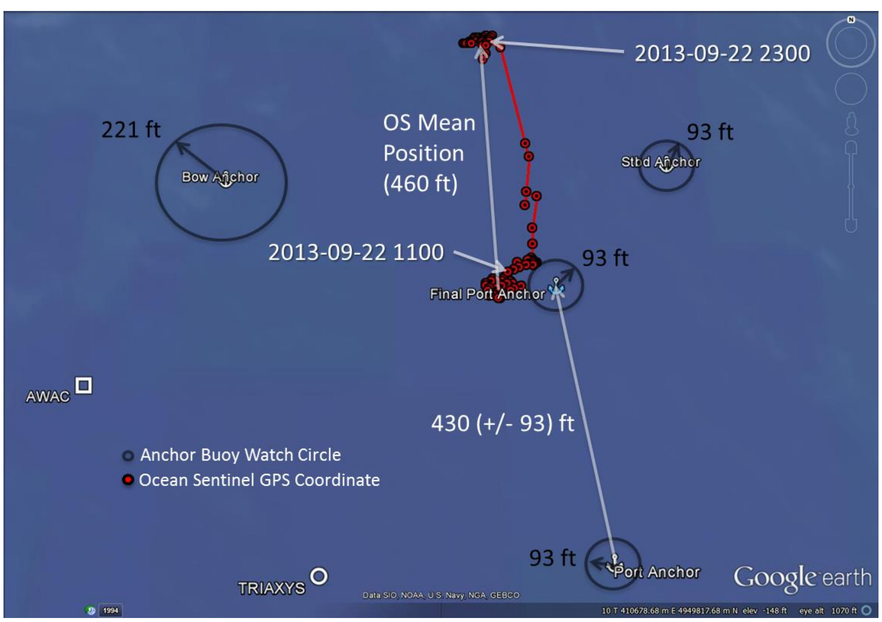


Figure 81: Ocean Sentinel Anchor Movement

6.4.2 Load Cell Damage

On 9/30/2013 the cables connecting both bow load cells to the CompactRIO DAS were damaged, and the load cells began providing inaccurate data. The ½ in (1.3 cm) conduit broke where it came out of the 1 in (2.5 cm) conduit near the end of the yoke, most likely due to abrasion and bending around the 1 in (2.5 cm) conduit. The individual wires in the cables were worn down to the conductors, most likely causing a short circuit through sea water (see Figure 82). It is difficult to assess how long the abrasion and bending were going on, but it's clear from the data that the short circuit began in both load cells on 9/30/2013. Therefore, data from the bow load cells after 9/29/2013 are not used in this study. A brief summary of the data analysis is given below.

- Bow load cell #1
    - Began showing negative values on 9/30/2013 from 0300-0600
        - Likely due to a short circuit through sea water between the excitation and signal conductors
    - Began showing shock loads of 160,000+ lb (711.7 kN) on 10/1/2013 from 0300-0600
        - Most likely occurred when the two exposed conductors made contact during cable twisting/flexing
    - Showed shock loads and negative values for rest of deployment
- Bow load cell #2
    - Began showing negative values on 9/30/2013 from 0000-0300
        - Same probable cause as bow load cell #1
    - Showed negative values for remainder of deployment, and never showed shock loads

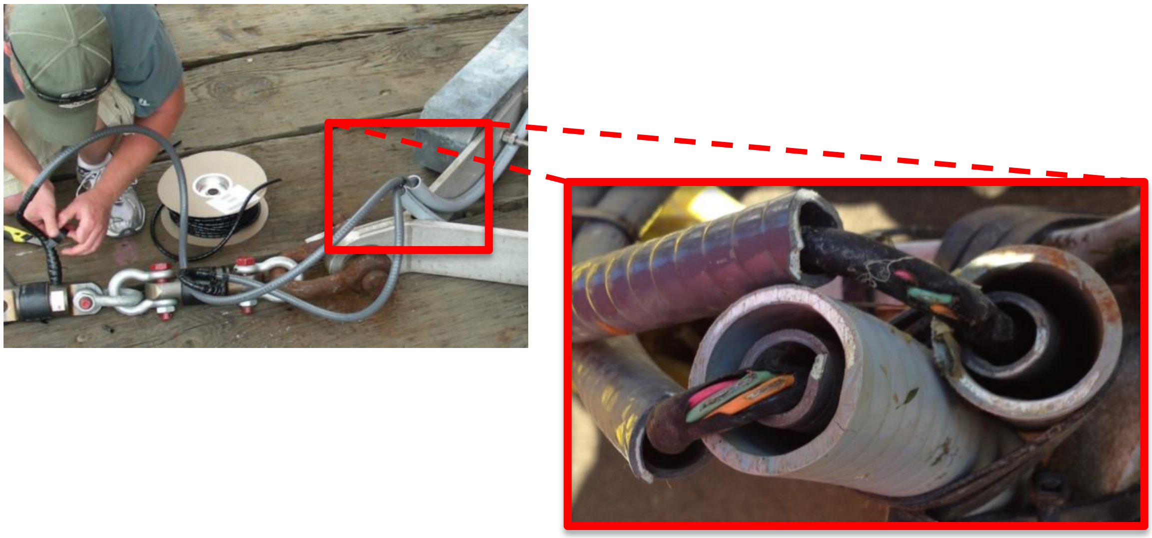


Figure 82: Bow load cell damage (Amon 2013)

6.5 Discussion

The Ocean Sentinel endured some unique environmental conditions during the 2013 deployment. Two large storms toward the end of September brought large waves, high wind velocities, and strong currents. A maximum wave height of H_{max} = 39.19 ft (11.94 m) was recorded by the TRIAXYS buoy, which was the largest summer wave recorded in the area during the last ten years (see Section 3.3). The Ocean Sentinel suffered minimal damage, and the two most notable events were the bow load cell failures and movement of the port anchor (see Figure 83).

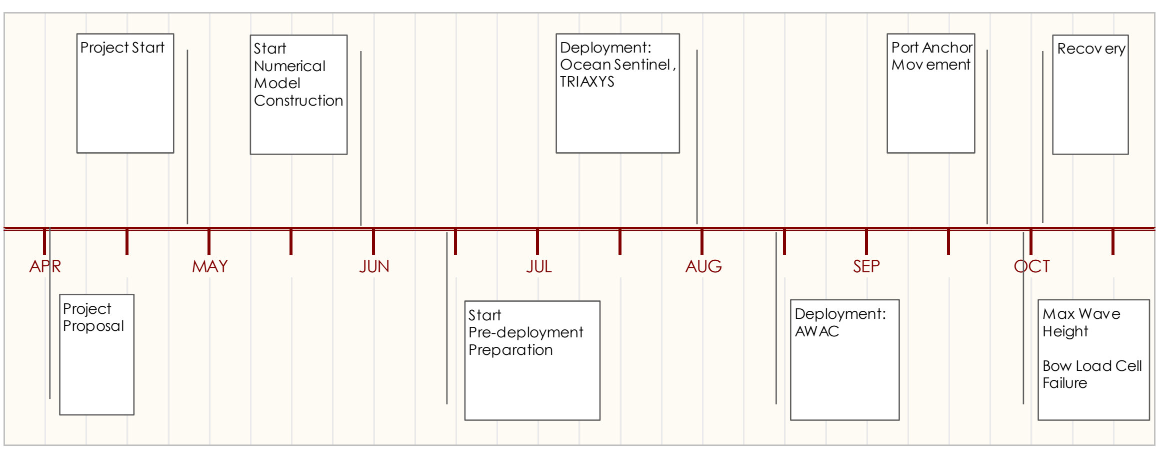


Figure 83: 2013 Project Timeline

Average mooring line loads during the deployment were minimal, with large spikes usually accompanying larger wave events. Higher loads can also be attributed to increases in the surface current, especially in the beginning of the deployment. It's clear from the data that the port and bow lines consistently endured larger forces than the starboard line. The starboard line was observed to be slack several times throughout the deployment in pictures from the Ocean Sentinel's onboard cameras. This loading scheme may be attributable to larger wave events approaching from the southwest, and the dominant current approaching from the south.

Damage to the bow load cell cables eventually caused inaccurate measurements, rendering data from these load cells unusable after 9/29/2013. Unfortunately this was before the biggest storm and mooring line loads of the deployment, so there may have been higher-than-recorded forces in the bow line.

The Ocean Sentinel dragged its port anchor approximately 430 ft (131 m), which is considered a minor mooring system failure. However, in a typical deployment with a WEC this may have been a major incident, resulting in damage to the umbilical cable or a buoy-to-buoy collision.

7 Model Correlation

With over two months of field data in this study, there were many opportunities for comparison with the numerical model. However, given the limited computer power and time required for numerical simulations, only two cases were compared for this study. The first case was an operational condition, which represented the typical environmental conditions experienced by the Ocean Sentinel during the deployment. The date and time period were chosen primarily by the wave climate and mooring line loads, with current and wind as secondary parameters. The second case was the day the Ocean Sentinel dragged its port anchor. A time period was chosen before the Ocean Sentinel moved outside of its watch circle to compare actual mooring line forces with the numerical model, and use the model to estimate forces on the port anchor.

7.1 Model Validity

The numerical model as it is currently built is only considered valid for comparison with field data from this study from 7/30/2013 – 09/22/2013 (before mid-day). Since the Ocean Sentinel dragged its port anchor on 9/22/2013, the model would need to be redesigned for comparison with data after this date to account for the new anchor position. The anchors are not built in the current version of the model (mooring chains are connected directly to the seabed), so forces at these locations do not account for movement of the anchors or friction of the anchors with the seabed.

7.2 Analysis Methods

Statistics and spectral analysis were used to analyze the mooring line forces from the field observation and the numerical model. The methods used are explained below.

7.2.1 Statistics

- F_{avg} – the mean force in the record
- $F_{1/3}$ – the mean of the highest one-third of the forces in the record
- $F_{1/10}$ – the mean of the highest one-tenth of the forces in the record
- F_{max} – the maximum force in the record

- Difference (bow) $= \dfrac{F_{OrcaFlex} - \left(\frac{F_{Loadcell\ 1} + F_{Loadcell\ 2}}{2}\right)}{\left(\frac{F_{Loadcell\ 1} + F_{Loadcell\ 2}}{2}\right)} \cdot 100$ (5)

- Difference (port/starboard) $= \dfrac{F_{OrcaFlex} - F_{Loadcell}}{F_{Loadcell}} \cdot 100$ (6)

7.2.2 Spectral Analysis

A MATLAB script written by Dave Newborn was used to produce the force spectra (PSD – Power Spectral Density) plots in this section. The mean was taken out of each time history when plotting the spectra, and the trend was removed using a Window Function. Each spectrum was band-averaged using 38 degrees of freedom. The f^{-3} parameter shown in each spectrum is the slope of the roll-off.

7.3 Case 1: Operational Condition

The time period on 8/24/2013 from 1240–1300, was chosen for Case 1 because environmental conditions and mooring line loads were close to average deployment values.

7.3.1 Environmental Conditions

Environmental conditions on 8/24/2013 from 1240–1300 were measured with the TRIAXYS buoy and sensors onboard the Ocean Sentinel, and were input into to the numerical model. The wave spectra plot for this time is shown in Figure 84, and the current-depth profile is shown in Figure 85. Values for significant wave height, significant wave period, dominant wave direction, surface current, and wind were:

- H_s = 5.33 ft (1.62 m)
- T_s = 7.90 s
- Dominant Wave Direction = 263° (from this direction)
- Surface Current = 0.148 knots (0.076 m/s), to 296°
- Wind = 1.56 knots (0.80 m/s), from 34°

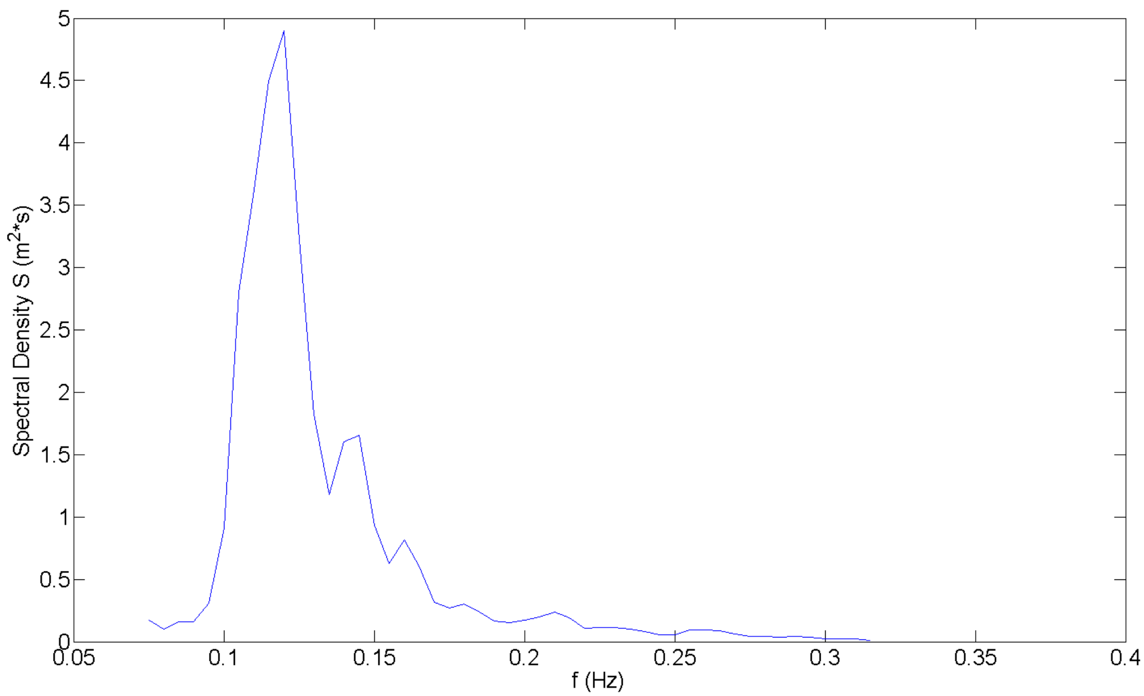
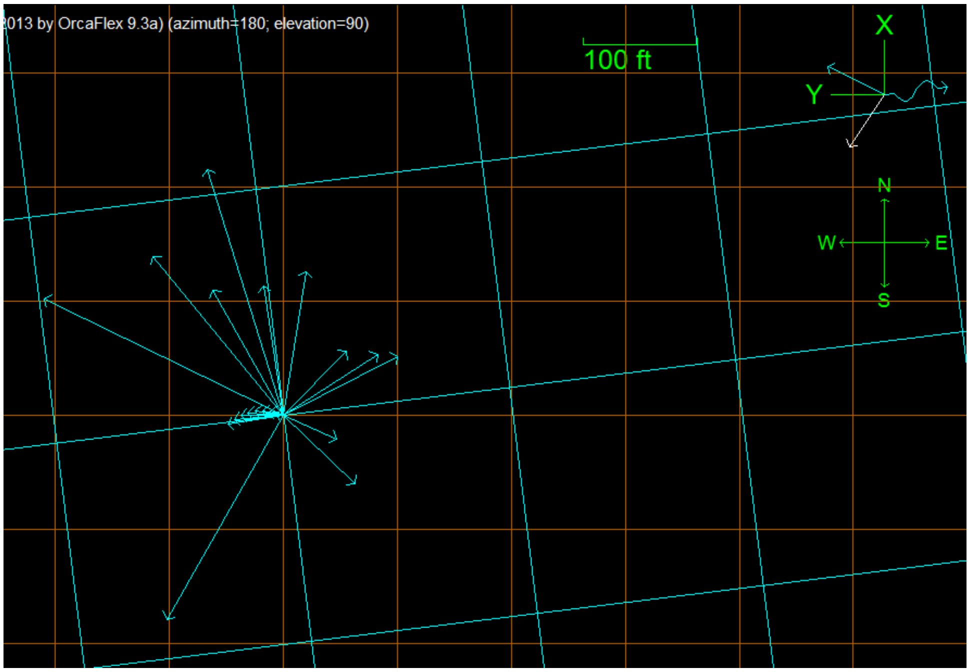


Figure 84: Wave Spectra, 8/24/2013 1240-1300



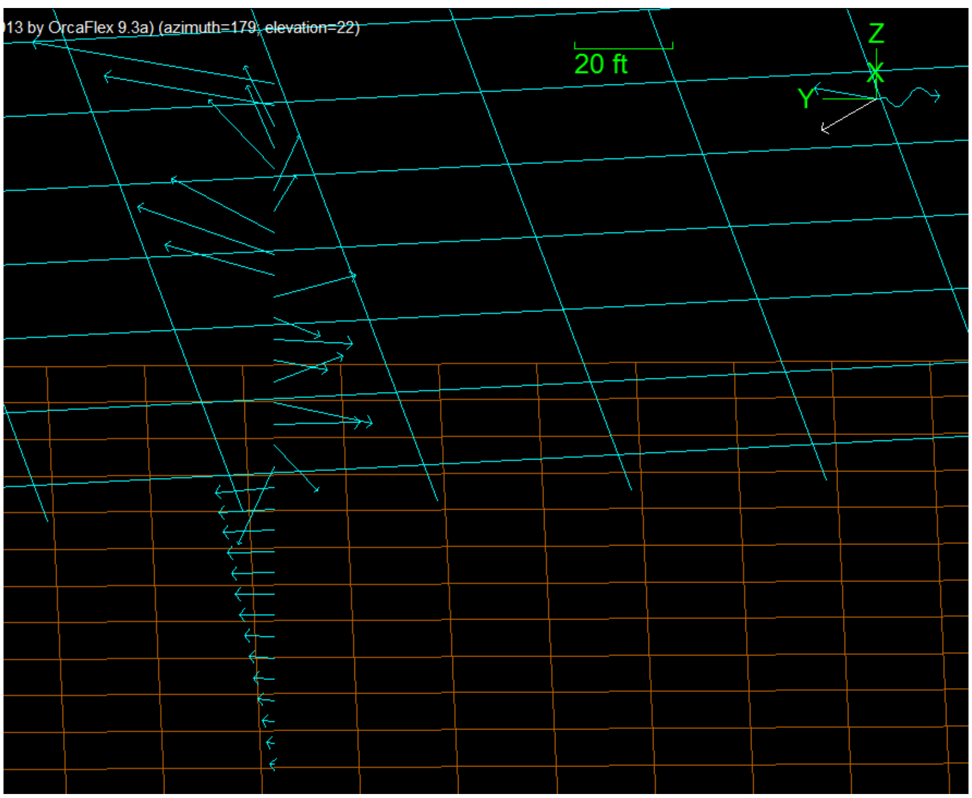


Figure 85: Current profile, 8/24/2013 1240-1300. Top panel – plan view, bottom panel – 3D view.

7.3.2 Mooring Line Loads

The actual mooring line tension loads on 8/24/2013 from 1240-1300 are shown below in comparison with results from the numerical model. Tension force statistics and the percent difference between numerical results and field data are shown in Table 7. Time histories and tension spectral plots are shown in Figures 86-91.

Table 8: Mooring Line Tension Statistics, 8/24/2013 1240-1300

Bow				
	F_{max} (lb)	$F_{1/10}$ (lb)	$F_{1/3}$ (lb)	F_{avg} (lb)
Load Cell 1	413.81	368.02	350.45	324.13
Load Cell 2	383.43	339.08	321.38	294.68
OrcaFlex	1221.00	683.3	562.16	413.99
Difference	206.31%	93.27%	67.35%	33.80%

Port				
	F_{max} (lb)	$F_{1/10}$ (lb)	$F_{1/3}$ (lb)	F_{avg} (lb)
Load Cell	470.97	247.84	182.15	112.54
OrcaFlex	1379.05	584.50	473.87	334.92
Difference	192.81%	135.84%	160.15%	197.60%

Starboard				
	F_{max} (lb)	$F_{1/10}$ (lb)	$F_{1/3}$ (lb)	F_{avg} (lb)
Load Cell	375.77	188.88	142.94	99.26
OrcaFlex	2299.84	604.29	412.78	209.66
Difference	512.03%	219.93%	188.78%	111.22%

7.3.2.1 Bow Line Data

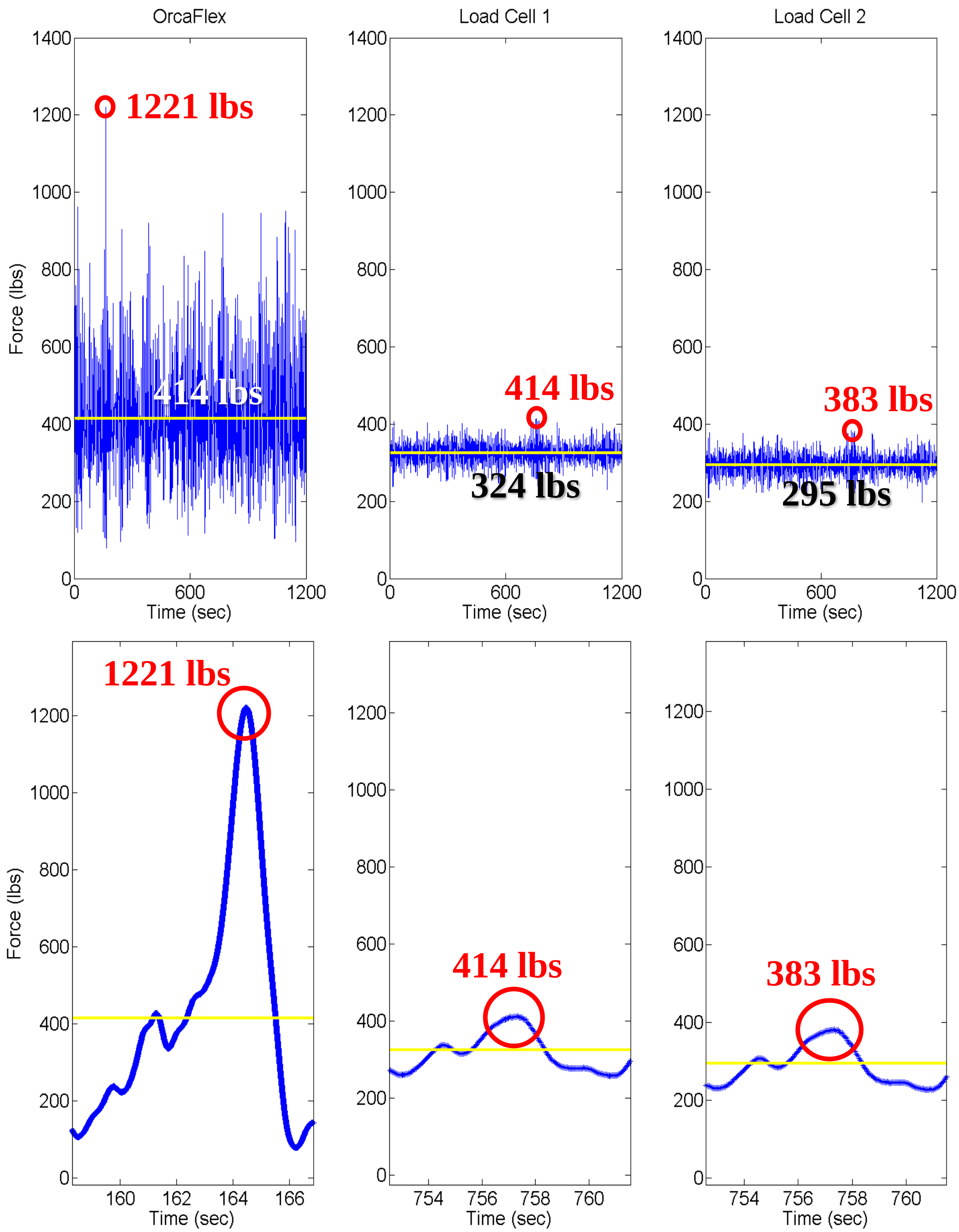


Figure 86: Bow Line Tension Time History, 8/24/2013 1240-1300

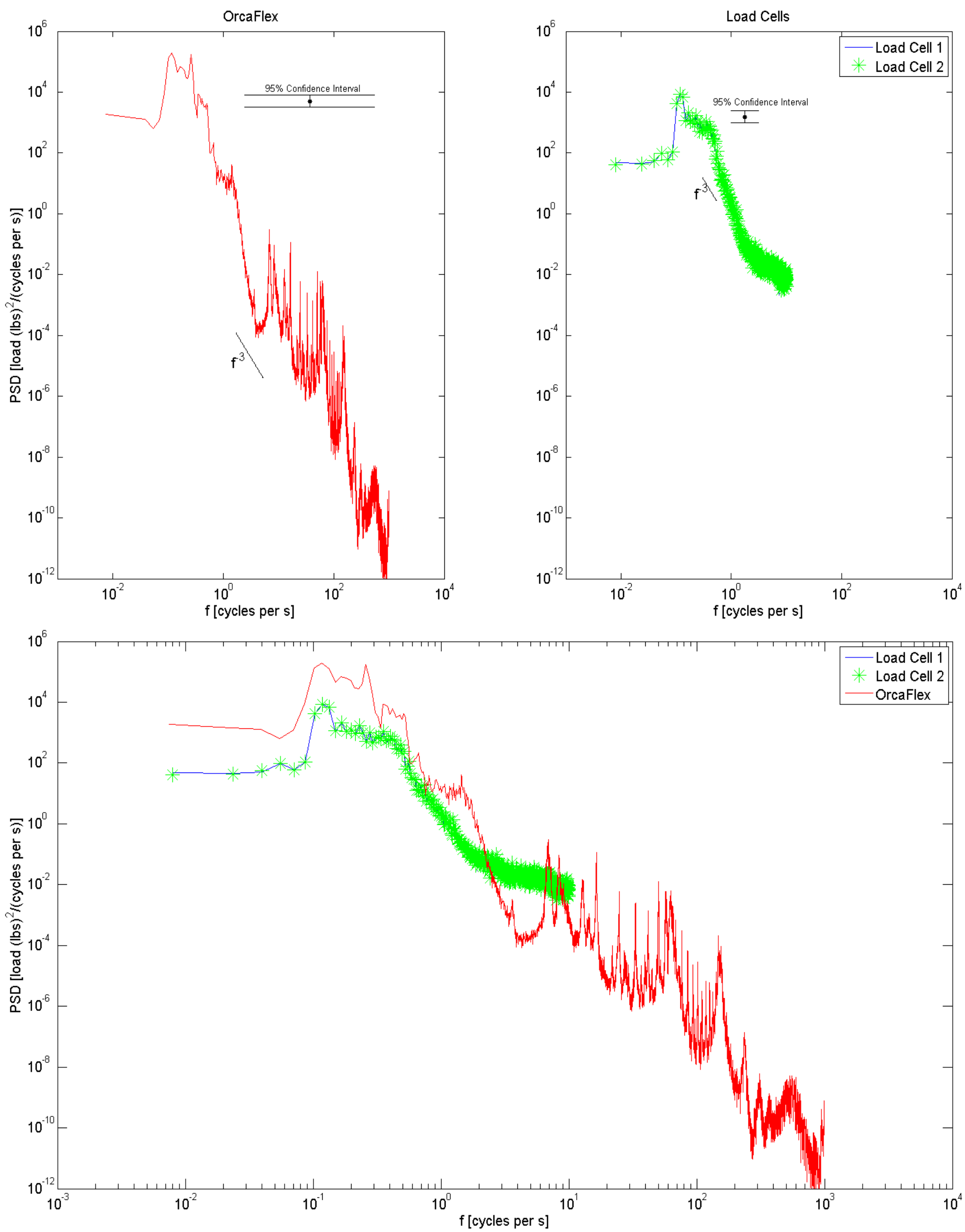


Figure 87: Bow Line Tension Spectra, 8/24/2013 1240-1300

7.3.2.2 Port Line Data

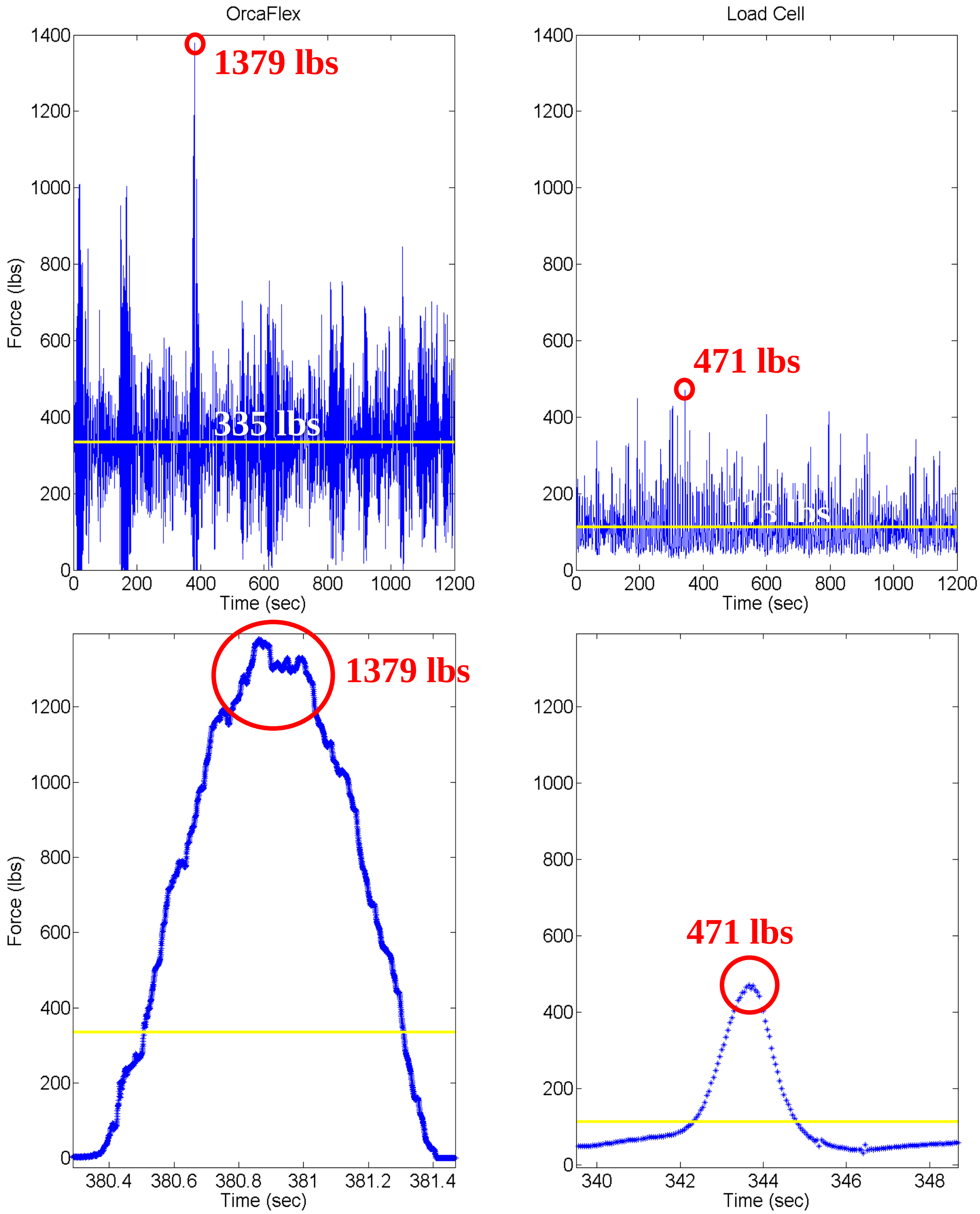


Figure 88: Port Line Tension Time History, 8/24/2013 1240-1300

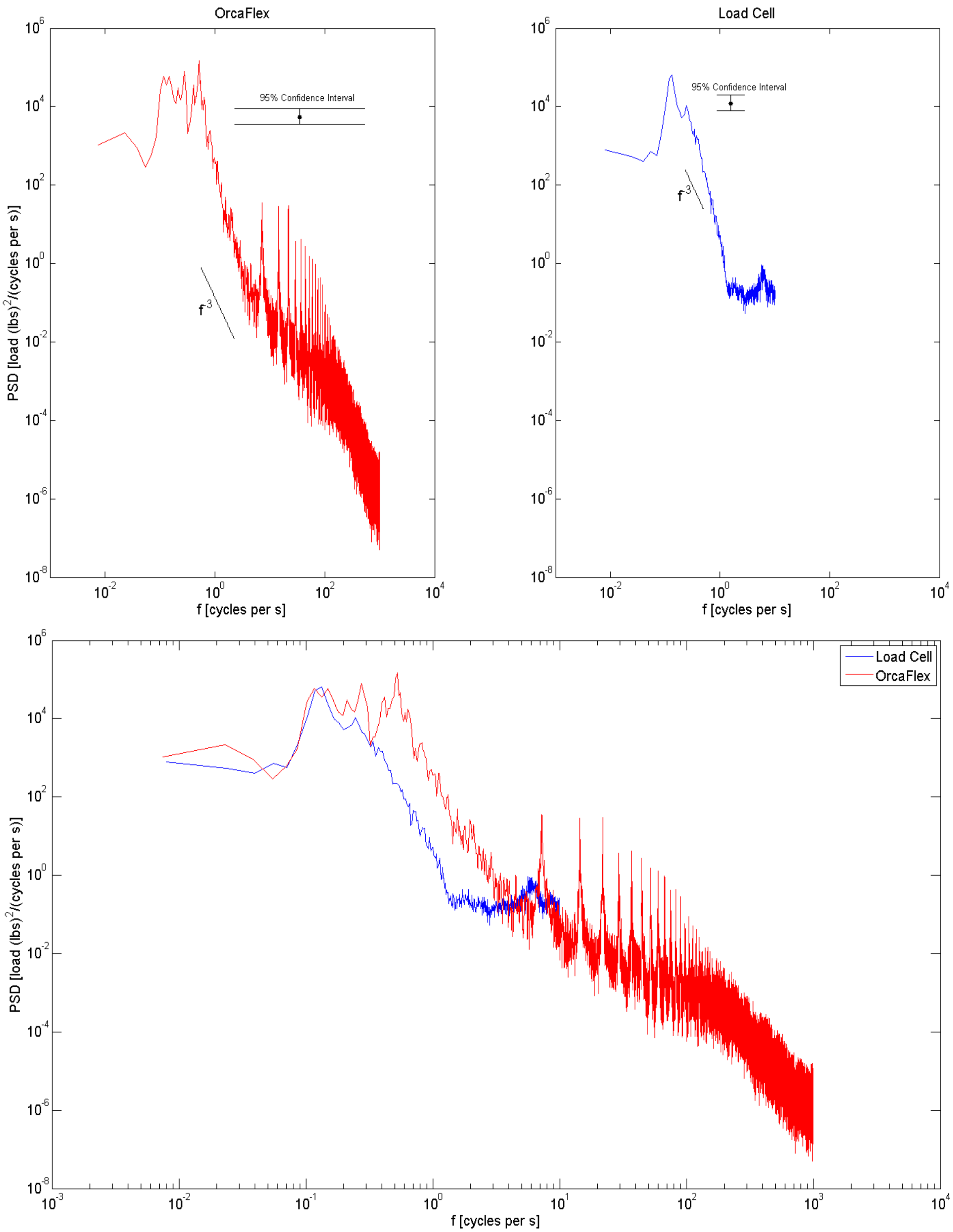


Figure 89: Port Line Tension Spectra, 8/24/2013 1240-1300

7.3.2.3 Starboard Line Data

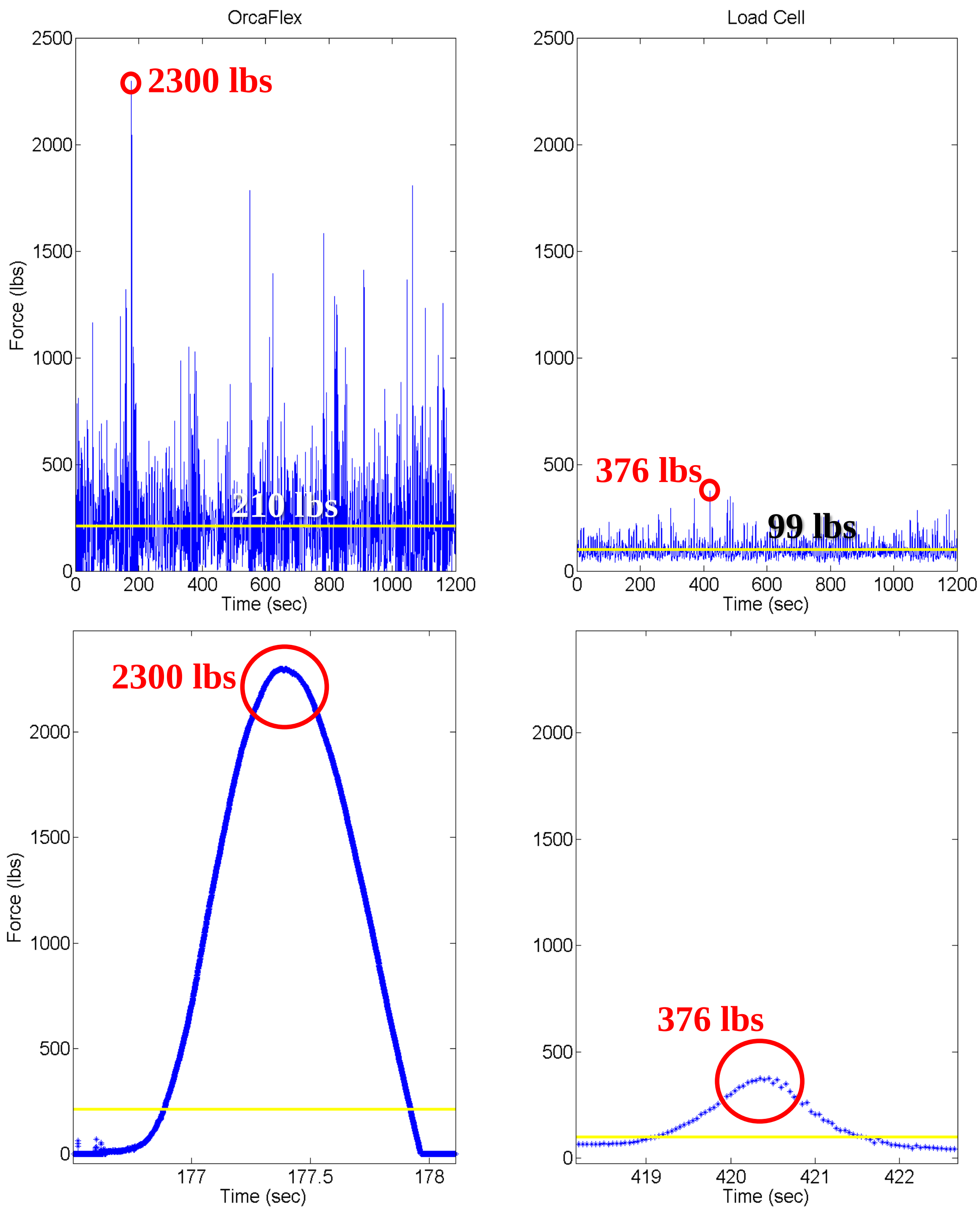


Figure 90: Starboard Line Tension Time History, 8/24/2013 1240-1300

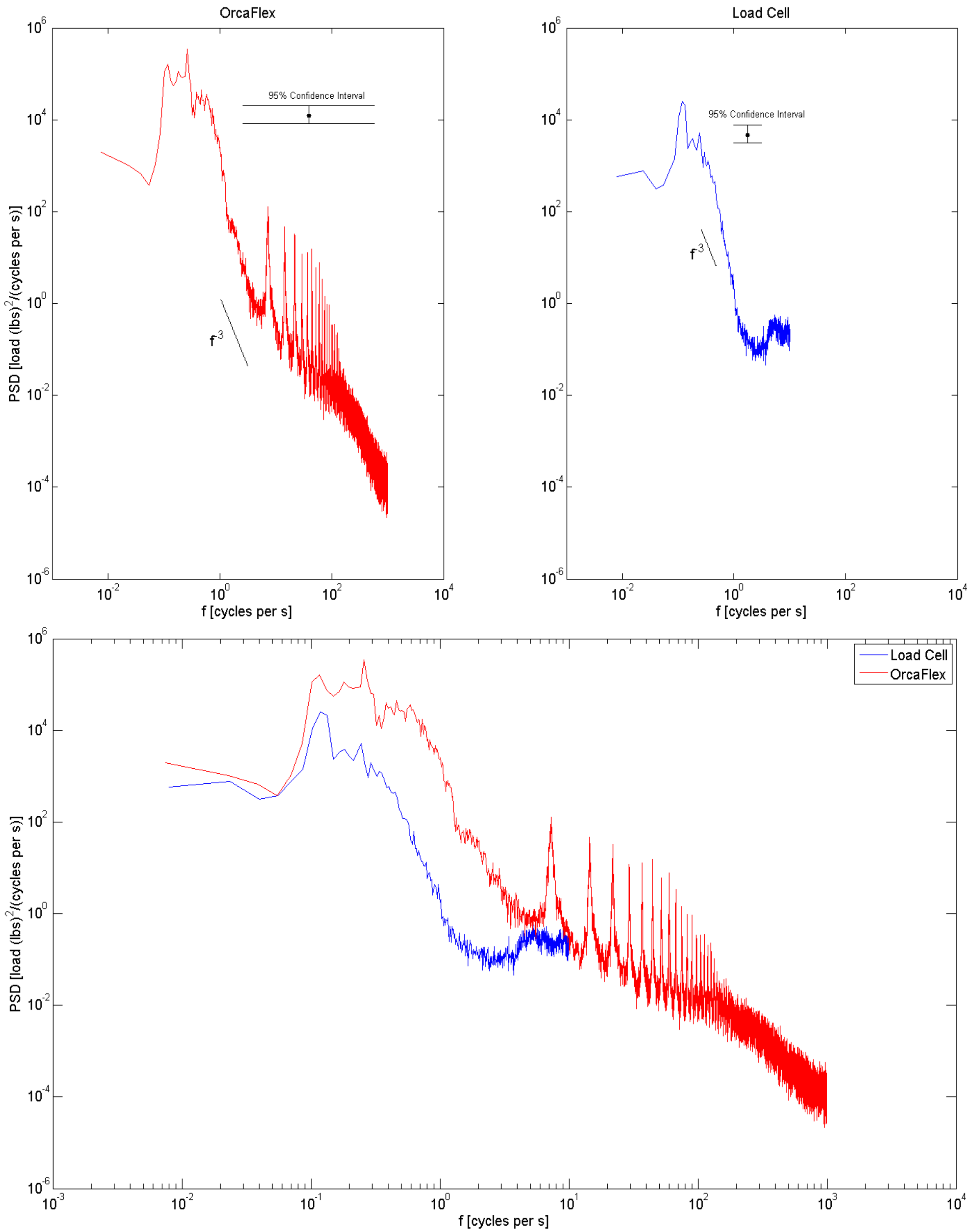


Figure 91: Starboard Line Tension Spectra, 8/24/2013 1240-1300

7.4 Case 2: Anchor Movement Day

The Ocean Sentinel began moving out of its watch circle on 9/22/2013 between 1000 and 1100, and most likely began dragging its port anchor during this time. Therefore, the time period of 1020 – 1040 on 9/22/2013 was chosen for further analysis and model simulation comparison.

7.4.1 Environmental Conditions

Environmental conditions on 9/22/2013 from 1020 – 1040 were measured with the TRIAXYS buoy and sensors onboard the Ocean Sentinel, and were used as inputs to the numerical model. The wave spectra plot for this time is shown in Figure 92, and the current-depth profile is shown in Figure 93. Values for significant wave height, significant wave period, dominant wave direction, surface current, and wind were:

- H_s = 6.63 ft (2.02 m)
- T_s = 10.20 s
- Dominant Wave Direction, from 272°
- Surface Current = 0.86 knots (0.44 m/s), to 342°
- Wind = 16.35 knots (8.40 m/s), from 178°

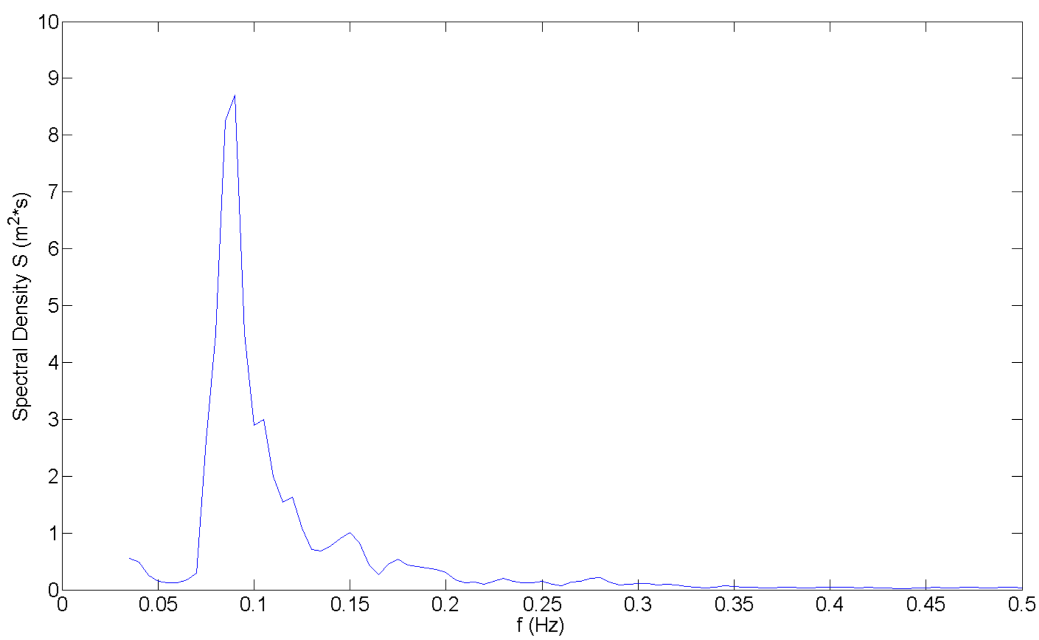


Figure 92: Wave Spectra, 9/22/2013 1020-1040

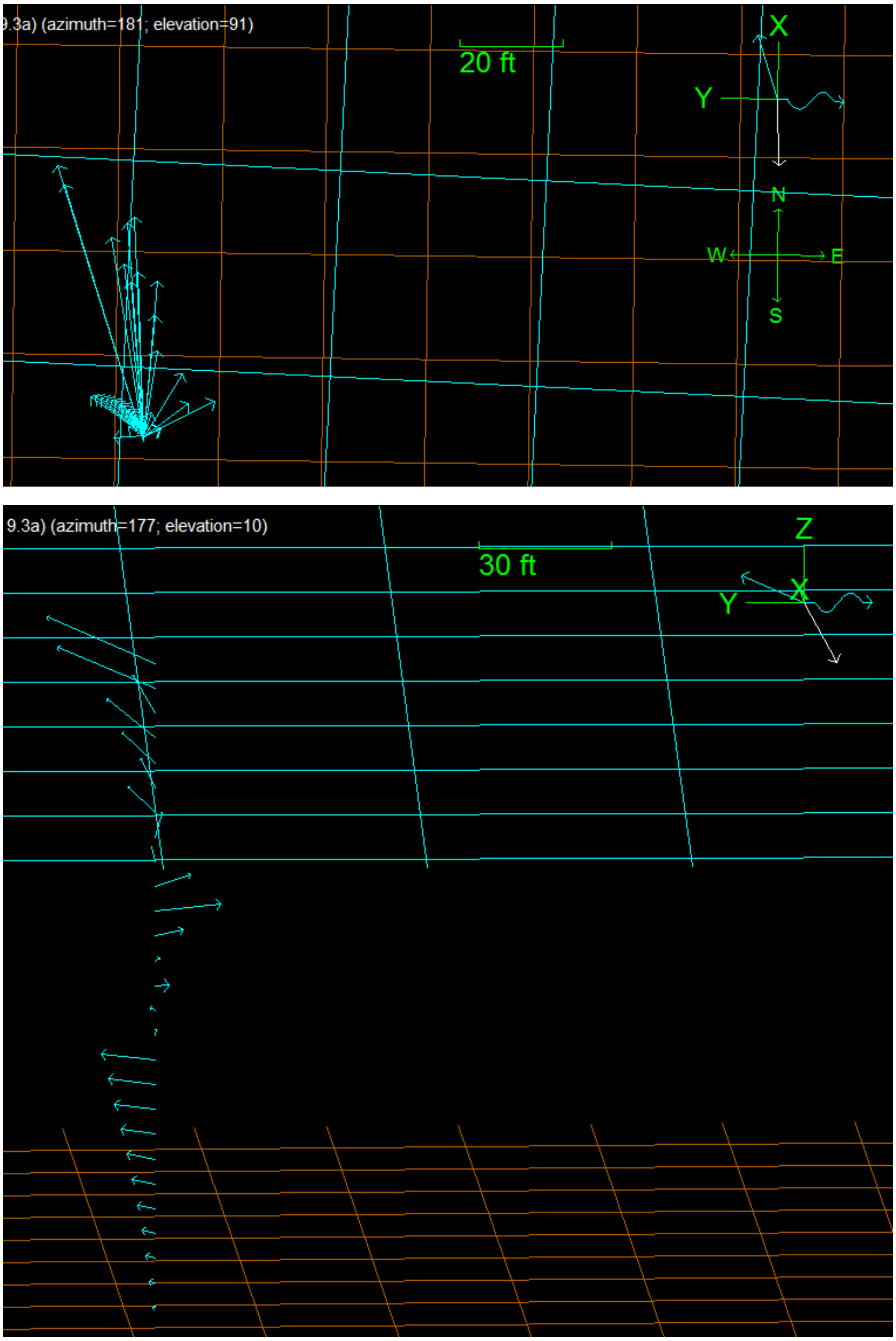


Figure 93: Current profile, 9/22/2013 1020-1040. Top panel – plan view, bottom panel – 3D view.

7.4.2 Mooring Line Loads

The actual mooring line tension loads on 9/22/2013 from 1020 – 1040 are shown below in comparison with results from the numerical model. Tension force statistics and the percent difference between numerical results and field data are shown in Table 7. Time histories and tension spectral plots are shown in Figures 94-99.

Table 9: Mooring Line Tension Statistics, 9/22/2013 1020-1040

Bow				
	F_{max} (lb)	$F_{1/10}$ (lb)	$F_{1/3}$ (lb)	F_{avg} (lb)
Load Cell 1	1010.98	677.89	567.85	441.36
Load Cell 2	970.78	638.88	529.05	402.68
OrcaFlex	1549.97	692.57	556.66	394.78
Difference	56.42%	5.19%	1.50%	6.45%

Port				
	F_{max} (lb)	$F_{1/10}$ (lb)	$F_{1/3}$ (lb)	F_{avg} (lb)
Load Cell	1715.58	1084.29	852.75	527.08
OrcaFlex	2096.71	1139.00	841.97	414.24
Difference	22.22%	5.05%	1.26%	21.41%

Starboard				
	F_{max} (lb)	$F_{1/10}$ (lb)	$F_{1/3}$ (lb)	F_{avg} (lb)
Load Cell	297.97	162.95	134.91	102.63
OrcaFlex	2808.81	1431.48	994.33	461.30
Difference	842.65%	778.48%	637.03%	349.48%

7.4.2.1 Bow Line Data

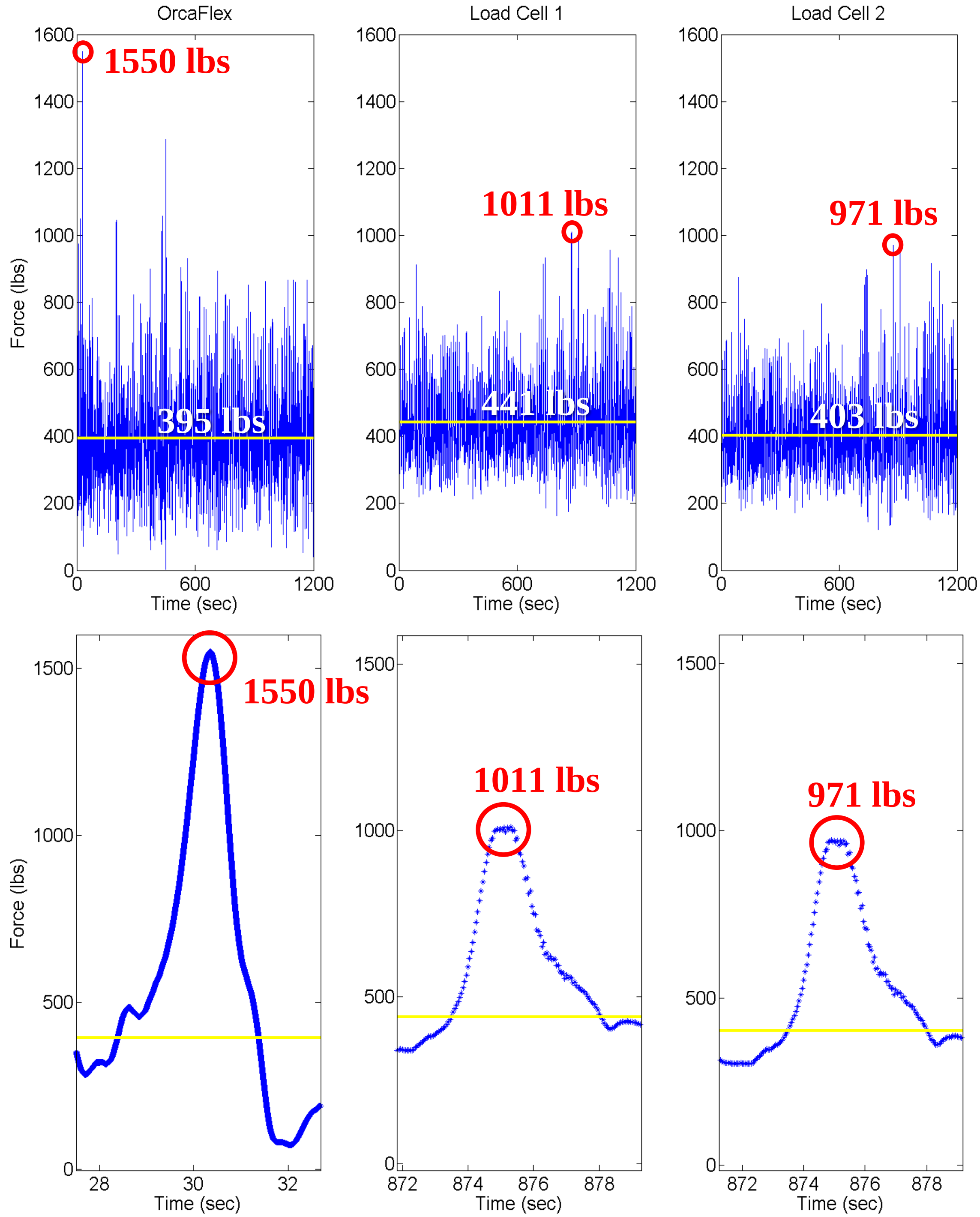


Figure 94: Bow Line Tension Time History, 9/22/2013 1020-1040

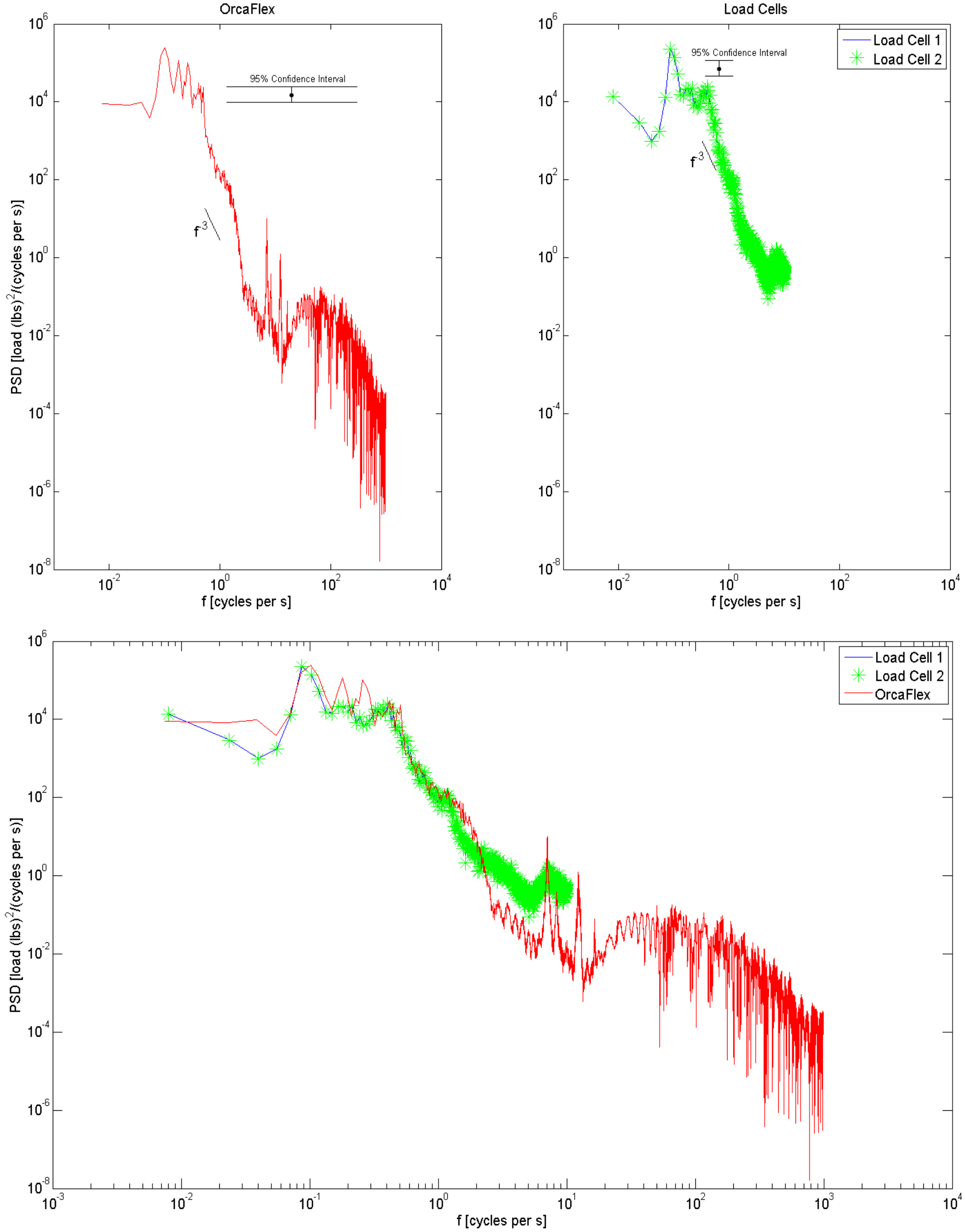


Figure 95: Bow Line Tension Spectra, 9/22/2013 1020-1040

7.4.2.2 Port Line Data

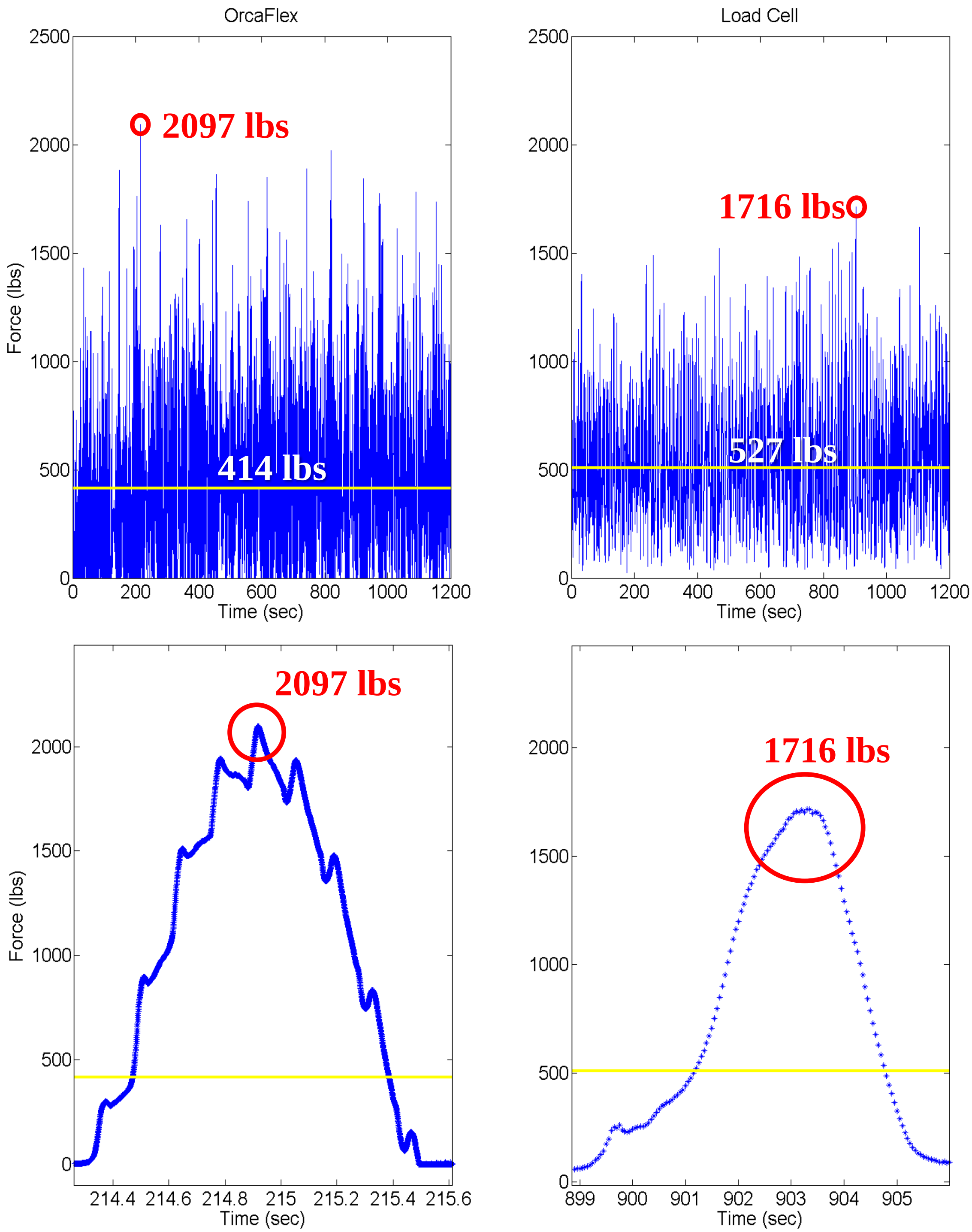


Figure 96: Port Line Tension Time History, 9/22/2013 1020-1040

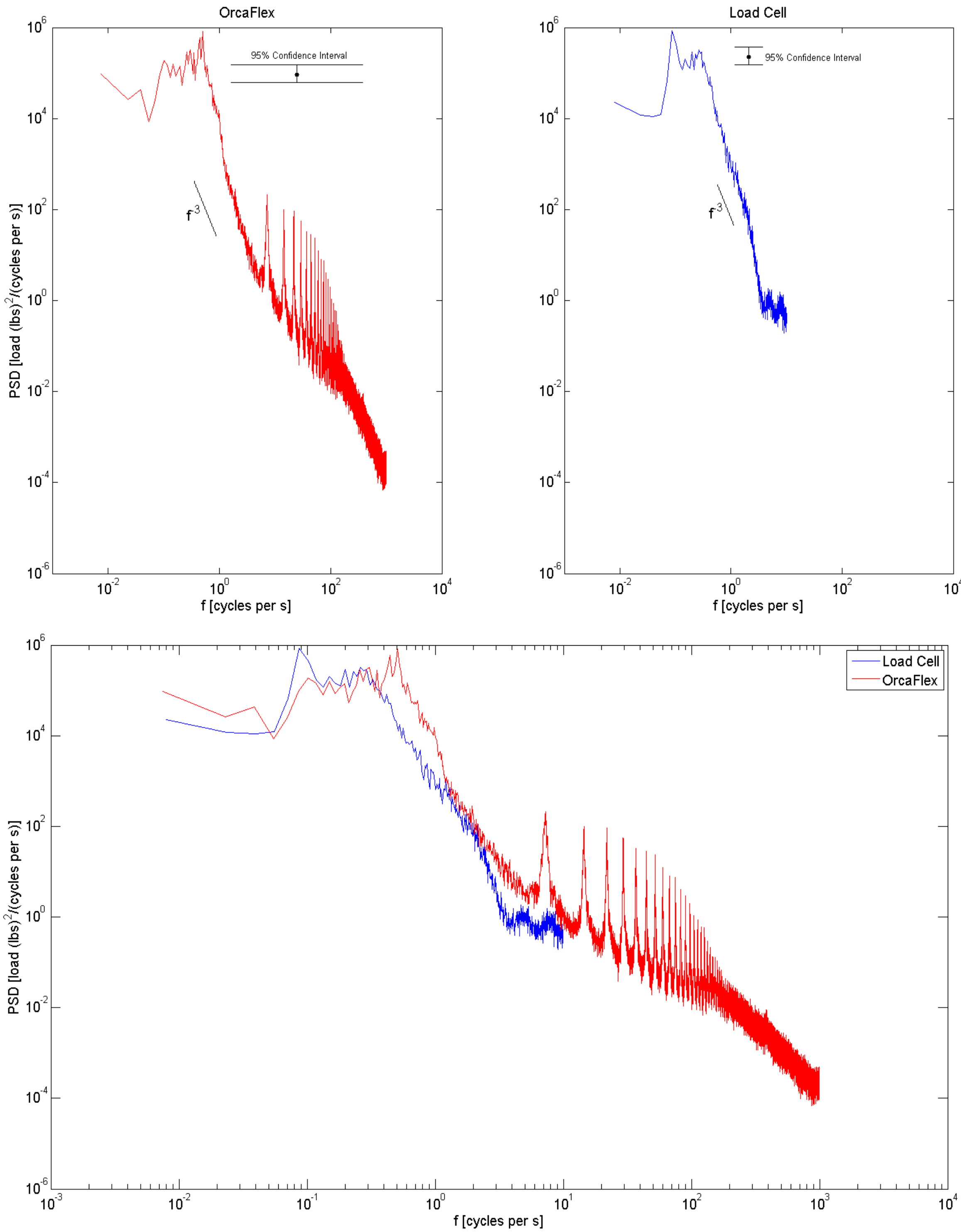


Figure 97: Port Line Tension Spectra, 9/22/2013 1020-1040

7.4.2.3 Starboard Line Data

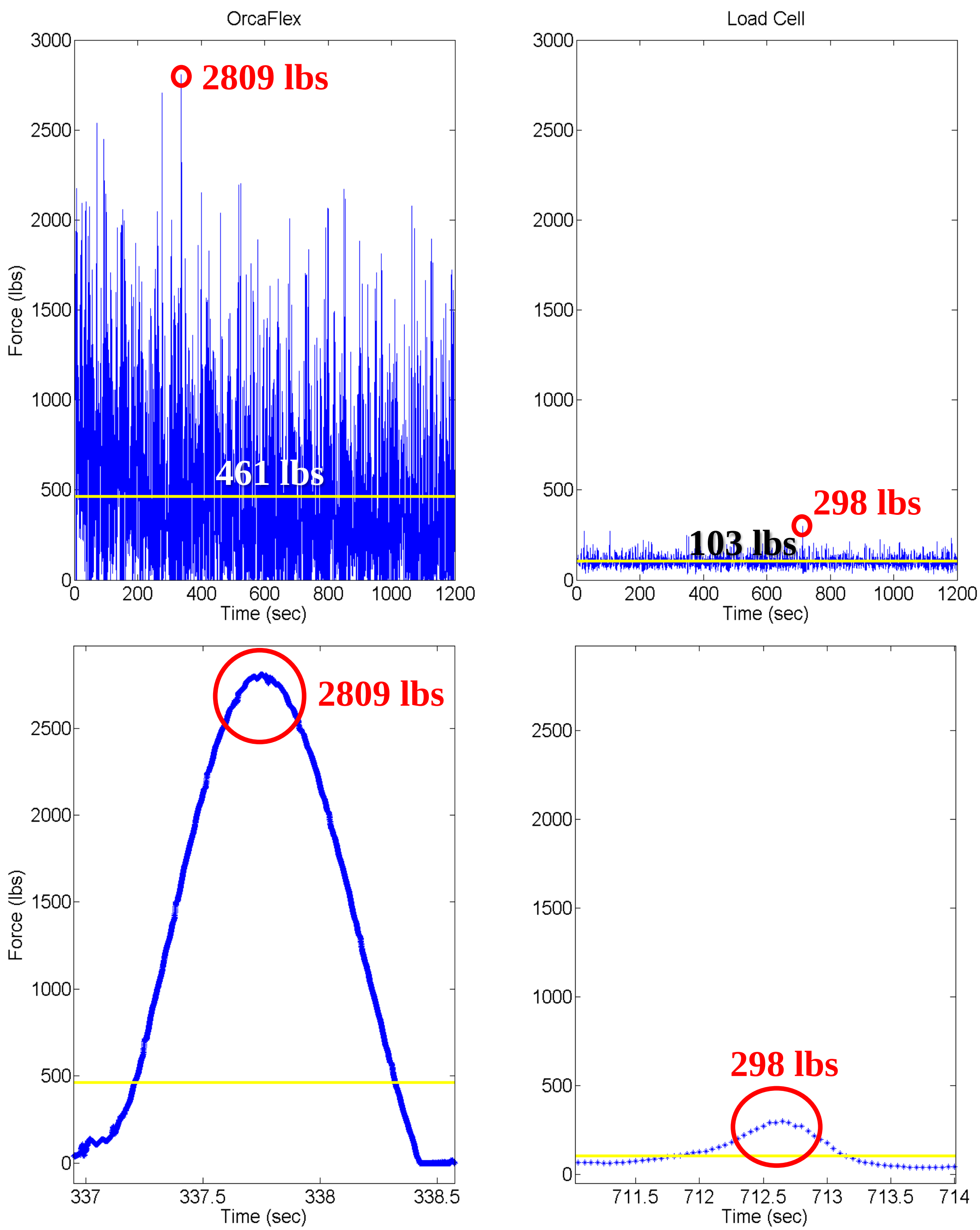


Figure 98: Starboard Line Tension Time History, 9/22/2013 1020-1040

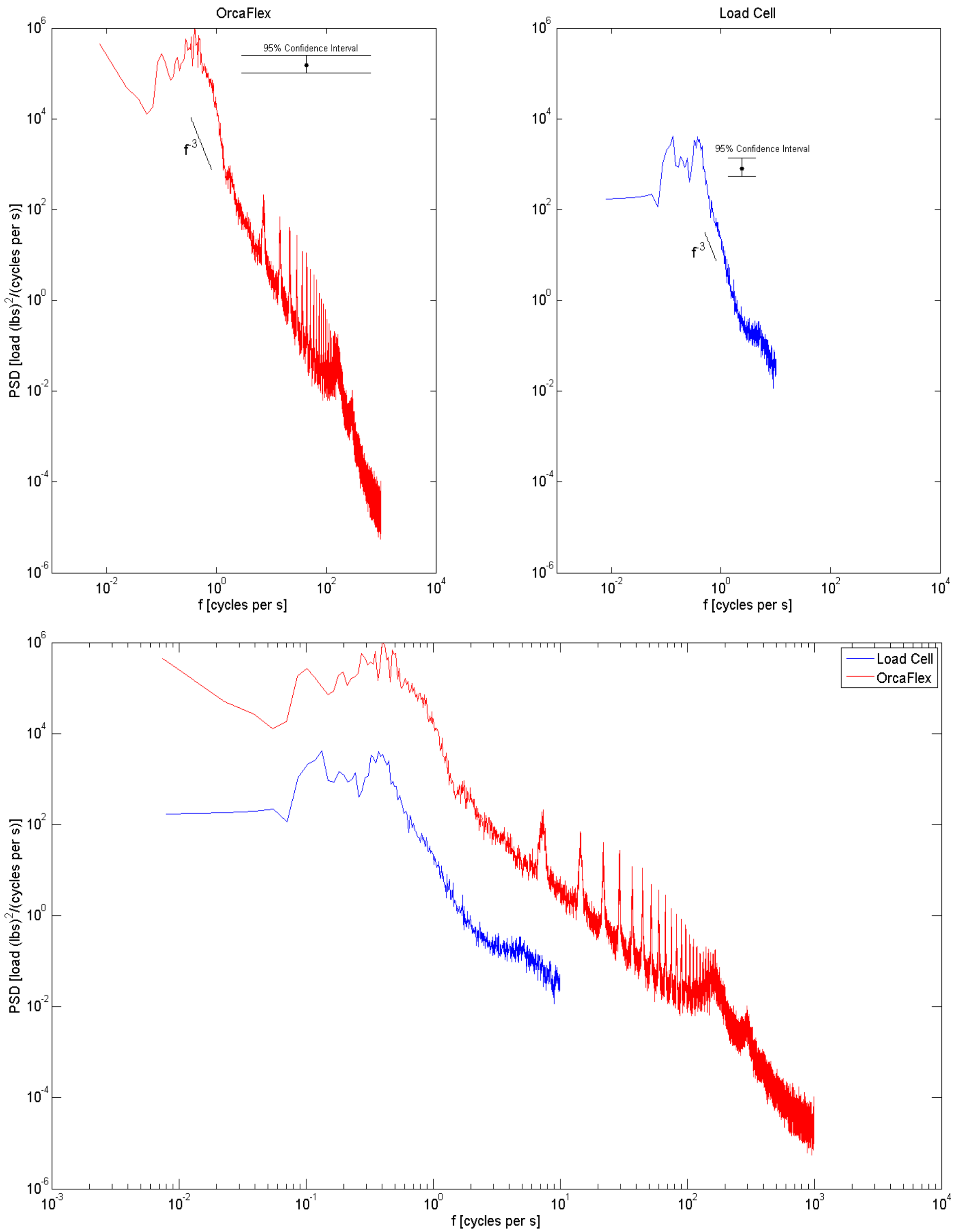


Figure 99: Starboard Line Tension Spectra, 9/22/2013 1020-1040

7.4.3 Port Anchor Load (Simulation)

The simulated forces on the port anchor imparted by the port mooring chain on 9/22/2013 from 1020 – 1040 are shown below. Tension force statistics are shown in Table 7. Time histories and tension spectral plots are shown in Figures 101 and 102, respectively.

Table 10: Simulated Anchor Force Statistics, 9/22/2013 1020-1040

Port Anchor				
	F_{max} (lb)	$F_{1/10}$ (lb)	$F_{1/3}$ (lb)	F_{avg} (lb)
Vertical Force (Z)	893.02	429.27	305.85	165.96
Lateral Force (XY)	1307.81	782.16	629.83	450.92

Figure 100 shows the simulated lateral force on the port anchor from 1020 – 1040 on 9/22/2013 (lower red line), as well as the lateral force required to move the port anchor during this time (upper blue line). The required lateral force was calculated by subtracting the simulated vertical force from the in-water weight of the port anchor (max xy drag force). See Appendix A.2 for the required lateral force calculation and equation.

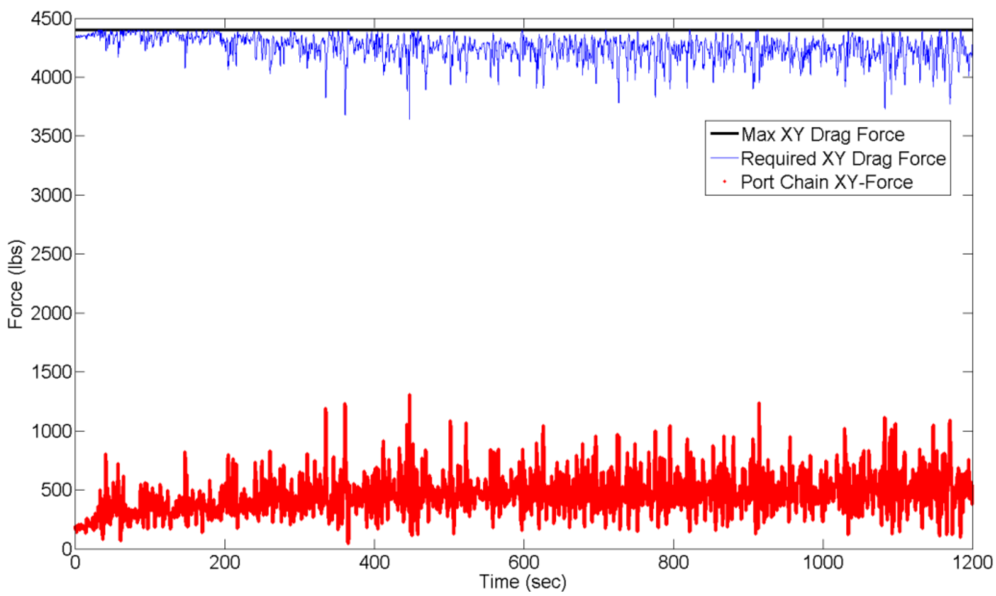


Figure 100: Port Anchor - Required and Simulated Force, 9/22/2013 1020-1040

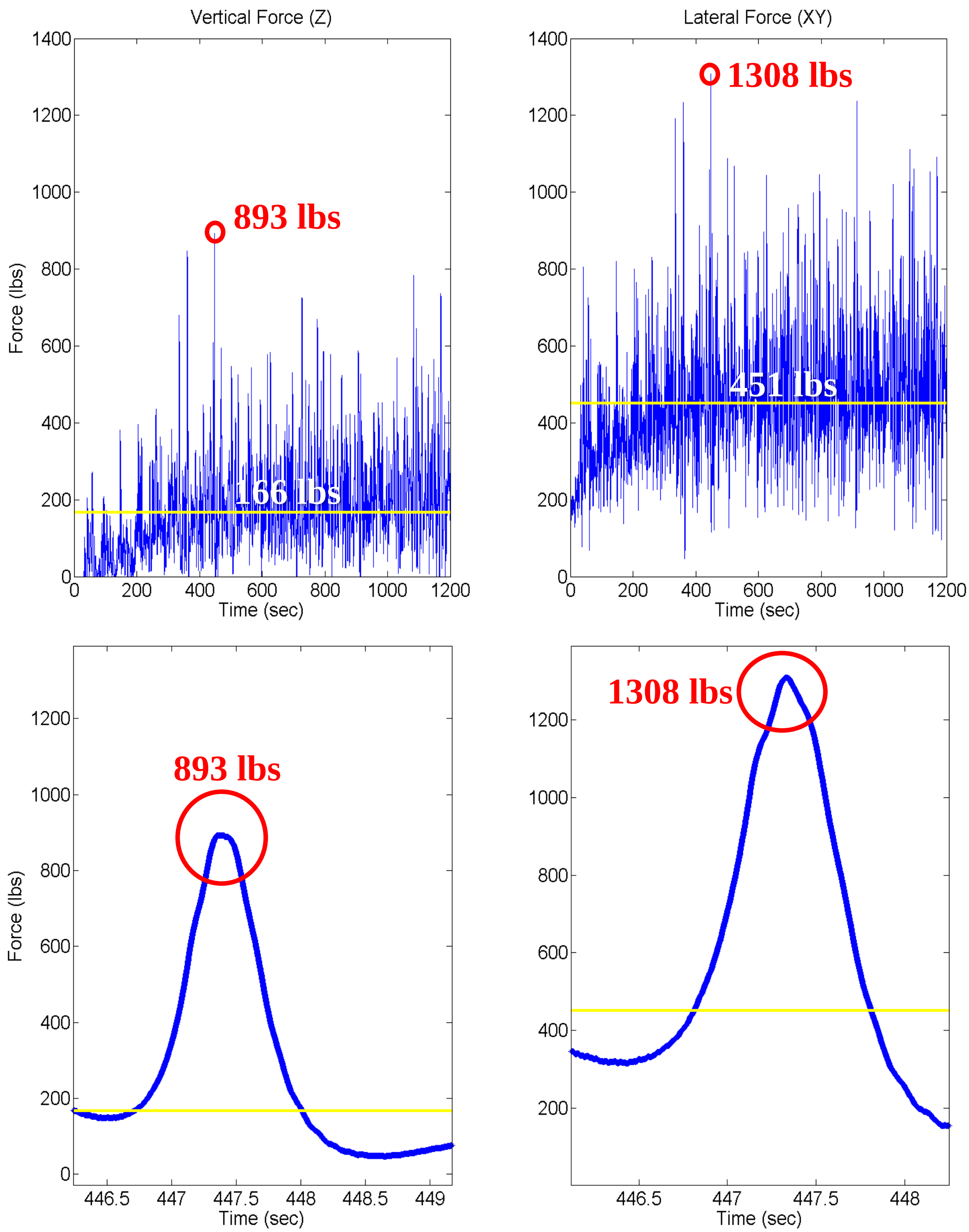


Figure 101: Simulated Port Anchor Force Time History, 9/22/2013 1020-1040

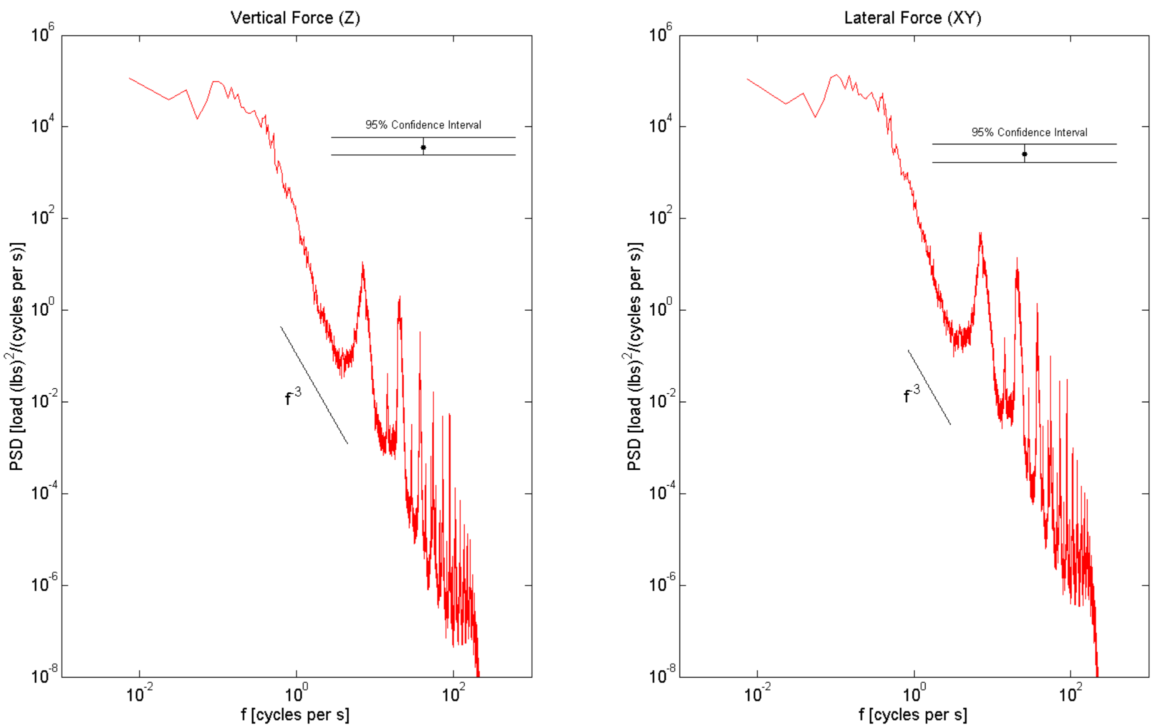


Figure 102: Simulated Port Anchor Force Spectra, 9/22/2013 1020-1040

7.5 Discussion

The numerical model showed mixed correlation with the field data. In almost all cases the model over-predicted forces in the mooring lines, but results varied widely.

The model did not show good correlation with the Case 1 (Operational Condition) field data, which was unexpected. This case had relatively calm environmental conditions, was well before the Ocean Sentinel dragged its anchors, and was expected to serve as a baseline. The numerical model over-predicted force magnitudes by 34% - 500% for this comparison. The shape of the spectral plots were reasonably well correlated in the lower frequencies, but were usually off by 1 – 2 orders of magnitude. The bow line showed the best correlation, and the starboard showed the worst. The reason behind the poor correlation during this time period is unknown, and will require further numerical simulation. However, one possible source of error is that the wave spectra had energy in frequencies outside of the model's defined RAO's for the Ocean Sentinel. OrcaFlex uses an interpolation routine to overcome this, but its effect on simulation results is unknown and requires further investigation.

The model showed good correlation with the Case 2 (Anchor Movement Day) field data, especially in the bow and port mooring lines. Both $F_{1/10}$ and $F_{1/3}$ for the model were within 5.2% of actual loads, with greater differences between the average and peak forces. The spectral plots for both of these mooring lines were also well correlated. The model did not show good correlation with the starboard line, with statistical forces off by 350 – 843%. The spectral plots had similar shapes, but were off by 2 – 4 orders of magnitude. The source of error in the starboard mooring line is unknown; however, one possibility is that the Ocean Sentinel already began dragging its port anchor during this time, and the starboard line became slack. The model showed forces too low to move the port anchor during this time, so the anchor may have been moved in small increments before/after this time. There are a number of possibilities as to how/when the Ocean Sentinel dragged its port anchor, and why model forces in the starboard line were higher than actual loads. These possibilities require further investigation.

7.6 Uncertainty

There are a number of uncertainties that must be taken into account when comparing the field data and numerical results in this study. These uncertainties lie both within the field measurements and the numerical model.

7.6.1 Field Measurements

The actual anchor locations on the seabed represent the largest uncertainty in the field observation. The anchors were deployed at pre-planned GPS coordinates, as explained in Section 4.3.5.1; however, they do not end up in the exact planned location on the seabed, primarily due to the method of placement.

Once the R/V PACIFIC STORM was close to the planned GPS coordinate, the “drop” command was called, and the winch operator began lifting the tip-plate. There was roughly a 5-sec delay between the drop command and when the anchor actually splashed the water. Upon splashing the “mark” command was used on the Garmin GPSMAP 78 to get the “actual” GPS coordinate of the anchor, which is accurate to 10ft. There was approximately a 2-sec delay between anchor splash and the GPS coordinate being recorded. Since the vessel was moving at approximately 1.5 knots (2.53 ft/s, 0.77 m/s), this 2-sec delay resulted in 5 ft (1.5 m) of distance. The surface current on anchor deployment days was approximately 3 knots (5.06 ft/s, 1.54 m/s), so assuming an average current in the water column of 1.5 knots, and the anchor moving through the water column at terminal velocity, the anchor could have drifted approximately 22 ft before landing on the seabed (see Appendix A.2 for calculation). Adding all of this up, the anchor location on the seabed could differ from the “actual” recorded GPS coordinate (which was input into the numerical model for anchor locations) by approximately 37 ft (11 m).

Other possible sources of uncertainty that may require further investigation include the TRIAXYS environmental data, the load cell data, and DAS sampling rates.

7.6.2 Numerical model

There are a number of possible sources of uncertainty in the numerical model that could affect simulation results. A brief sensitivity analysis was done during the model development phase, but there was not enough time or computing power available to accurately quantify model sensitivities during the comparison phase. Environmental conditions and simulation times during the comparison phase were very different than those used during the model development phase, so many simulations would be needed for a complete sensitivity analysis.

The model is not a complete representation of the Ocean Sentinel mooring system, because some of the components are not modeled, including: shackles, swivels, load cells, and anchors. Of these components, the anchors probably have the greatest effect on simulation results. There are also other model attributes that may require further study, including: line segmentation, integration method, and vessel RAO’s.

8 Recommendations

8.1 Mooring System

8.1.1 Design

The Ocean Sentinel mooring system was used in the same configuration for the 2012 and 2013 deployments. Overall the system has performed well by keeping the Ocean Sentinel properly oriented and within the test site. However, the mooring system experienced a minor failure during the 2013 deployment, and will need to be redesigned. Possible improvements include:

1. Use heavier gravity anchors, or add weight to the existing anchors. For either option a more dense material is recommended, such as steel or lead.
2. Replace the gravity anchors with drag anchors, or modify the existing anchors into Pearl Harbor anchors. This would require modifying the anchor deployment method.
3. Use three shots (89.9 ft, 27.4 m) of chain on the port and starboard mooring legs (similar to what is used on the bow leg), and move the anchor positions out. This recommendation could be used in conjunction with an anchor improvement.
4. Adjust the Ocean Sentinel deployment scheme so that the bow faces more southwest. Many of the largest waves came from the southwest, and hit the Ocean Sentinel broadside.
5. Do not use double conduit for cable protection, or do not terminate outer conduit near the yoke.

8.1.2 Deployment

This study documented the 2013 deployment of the Ocean Sentinel. Many of the same methods were used as the 2012 deployment and continue to work well, including: deploying anchors with the tip-plate, towing the Ocean Sentinel to Ship Ops and the test site, and using the RHIB for final placement of the Ocean Sentinel. Some methods that could be improved include:

1. Mooring line attachment. Install a winch on the stern of the Ocean Sentinel that could be used to pull tension in the mooring lines during deployment. This could be a hand winch, as long as it can lock and hold slack that has been taken up. This may require structural some modification to the Ocean Sentinel.
2. Pulling up the yoke. Install a winch on the bow of the Ocean Sentinel that could be used to haul up the yoke during towing. This could be a hand winch, as long as it can lock and hold slack that has been taken up. This may require some structural modification to the Ocean Sentinel.
3. Anchor Removal. Develop a plan for leaving the anchors at the NETS long-term. Deploying and retrieving the anchors for every deployment may be an inefficient use of resources. The plan should include permitting, maintenance and inspection cycles, and future deployment orientations.

8.2 OrcaFlex model

During the course of this study the numerical model was updated to reflect the as-deployed Ocean Sentinel buoy and mooring system, and preliminary simulations were used for comparison with field data. The focus was on the mooring lines and anchor locations, and there are many aspects of the model that were assumed to be accurate and not thoroughly investigated, including: the Ocean Sentinel buoy properties, yoke properties and behavior, and the surface buoys. The anchors were not built in the model, but it may be possible to model them using 6D buoys. Simulations may then show more accurate forces on the anchors, including friction with the seabed, and possibly anchor movement. Additionally a thorough sensitivity analysis should be conducted, which should include model properties, software characteristics, and simulations with multiple anchor locations that include uncertainty.

With some fine-tuning and further correlation to field data, the numerical model could be an important tool for the mooring system redesign and future study of Ocean Sentinel characteristics.

9 Conclusion

The three main objectives of this study were accomplished, which were:

1. Acquire a dataset of actual loads on the Ocean Sentinel mooring system.
2. Document the deployment and recovery process, and consolidate all pertinent information about the Ocean Sentinel.
3. Create an Ocean Sentinel numerical model, and run preliminary simulations to compare model predictions with field data.

The Ocean Sentinel survived unusually harsh environmental conditions during the 2013 deployment, and all environmental conditions and mooring line forces were successfully recorded. The deployment and recovery process have been recorded in this study, which can be used as a reference for implementing and improving future deployment and recovery operations. A numerical model of the Ocean Sentinel mooring system was created and preliminary simulations were run using actual deployment conditions. Model predictions of mooring line tension forces showed mixed results when compared to actual field data. Follow on work to this study will include verification and validation of the numerical model, as well as uncertainty quantification for the model and field data. The Ocean Sentinel mooring system may also be redesigned due to the minor mooring system failure during the 2013 deployment.

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APPENDICES

A. Calculations

A.1 NETS Shoaling Calculation

NDBC 46050

$h = 420 \text{ ft}$

$T_0 = 14.81 \text{ s}$
$\sigma_0 = 0.424 \text{ s}^{-1}$

$k = 0.0057 \text{ ft}^{-1}$
$L = 1{,}106.5 \text{ ft}$

$\frac{h}{L} = \frac{420}{1106.5} = 0.34$
(transitional water)

$C_1 = \frac{L}{T} = \frac{1{,}106.5 \text{ ft}}{14.81 \text{ s}}$

$C_1 = 74.71 \text{ ft/s}$

$C_0 = \frac{gT}{2\pi} = \frac{(32.2 \text{ ft/s}^2)(14.81 \text{ s})}{2\pi}$

$C_0 = 75.90 \text{ ft/s}$

$n_1 = \frac{1}{2}\left(1 + \frac{2kh}{\sinh 2kh}\right)$

$n_1 = \frac{1}{2}\left[1 + \frac{2(0.0057 \text{ ft}^{-1})(420 \text{ ft})}{\sinh[2(0.0057)(420)]}\right]$

$n_1 = 0.540$

$C_{g_1} = n_1 C_1 = (0.54)(74.41 \text{ ft/s})$

$C_{g_1} = 40.173 \text{ ft/s}$

NNMREC test site

$h = 154 \text{ ft}$

$T_0 = 14.81 \text{ s}$
$\sigma_0 = 0.424 \text{ s}^{-1}$

$k = 0.0070$
$L = 893.76 \text{ ft}$

$\frac{h}{L} = \frac{154}{893.76} = 0.172$
(deep water)

$C_2 = \frac{L}{T} = \frac{893.76 \text{ ft}}{14.81 \text{ s}}$

$C_2 = 60.35 \text{ ft/s}$

$n_2 = \frac{1}{2}\left(1 + \frac{2kh}{\sinh 2kh}\right)$

$n_2 = \frac{1}{2}\left[1 + \frac{2(0.0070 \text{ ft}^{-1})(154 \text{ ft})}{\sinh 2(0.0070)(154)}\right]$

$n_2 = 0.753$

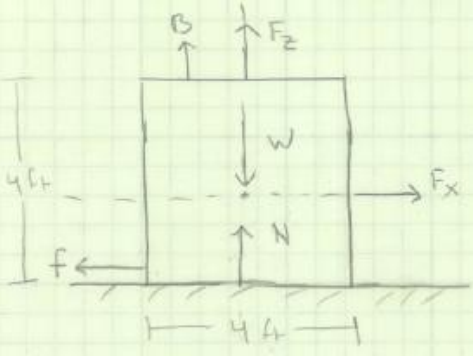
$C_{g_2} = n_2 C_2 = (0.753)(60.35 \text{ ft/s})$

$C_{g_2} = 45.45 \text{ ft/s}$

$$K_s = \sqrt{\frac{C_{g_1}}{C_{g_2}}} = \sqrt{\frac{40.173 \text{ ft/s}}{45.45 \text{ ft/s}}}$$

$\boxed{K_s = 0.940}$ - between Stonewall Banks and NNMREC test site

A.2 Anchor Calculations



* force locations are not considering moments

$\mu = 0.6$ - friction coefficient for concrete on sandy bottom (SST 2009, p.126)

$f = \mu N$

Equilibrium in z-dir

$F_z = 0$

$\Sigma F_x = F_x - f = 0$

$F_x = \mu N = (0.6)(5184\ lbf)$

$\boxed{F_x = 3110.4\ lbf}$ * horizontal force required to drag anchor when no vertical force is present

$V_c = 4ft \times 4ft \times 4ft = 64\ ft^3$

$\rho_{concrete} = 145\ lb/ft^3$

$\rho_{seawater} = 64\ lb/ft^3$

$W = \rho_c V_c = (145\ lb/ft^3)(64\ ft^3)$

$W = 9280\ lbf$

$B = \rho_{sw} V_c = (64\ lb/ft^3)(64\ ft^3)$

$B = 4096\ lbf$

Equilibrium (no external forces)

$F_z = F_x = 0$

$\Sigma F_y = B + N - W = 0$

$N = W - B = 9280 - 4096\ lbf$

$N = 5184\ lbf$ "in-water weight"

Velocity through water during deployment

$$V_t = \sqrt{\frac{2 W_{in\text{-}water}}{\rho_{sw} A C_D}} = \sqrt{\frac{2(5184\ lbf)}{\left(\frac{64\ \frac{lbm}{ft^3}}{32.2\ \frac{lbm \cdot ft}{lbf \cdot s^2}}\right)(16 ft^2)(1.05)}}$$

$V_t = 17.62\ ft/s$

$$Drift = \left(\frac{depth}{velocity}\right)(current) = \left(\frac{154\ ft}{17.62\ ft/s}\right)\left(2.53\ \frac{ft}{s}\right)$$

$\boxed{\text{Anchor Drift} = 22.11\ ft}$

Real Scenario

$\Sigma F_z = F_z + N + B - W = 0$

$N = W - B - F_z$ (until lift off)

$\Sigma F_x = F_x - \mu N = 0$

$F_x = \mu (W - B - F_z)$

$F_x = (0.6)(9280 - 4096 - F_z)$

$F_x = 3110.4 - 0.6 F_z$

$\Sigma F_y = F_y - \mu N = 0$

$F_y = \mu (W - B - F_z)$

$F_y = (0.6)(9280 - 4096 - F_z)$

$F_y = 3110.4 - 0.6 F_z$

$F_{xy} = \sqrt{F_x^2 + F_y^2} = \sqrt{(3110.4 - 0.6F_z)^2 + (3110.4 - 0.6F_z)^2}$

$F_{xy} = \sqrt{2}\,(3110.4 - 0.6F_z)$

$\boxed{F_{xy} = 4398.77 - (0.849)F_z}$

* force required in XY plane to drag anchor

A.3 Mooring Line Calculations

Synthetic Line Calculations

$SG = 1.2 \quad \rho_{sw} = 64\ \text{lb/ft}^3 \quad M = 0.6\ \text{lbs/ft}$

$\rho_r = 1.2\rho_{sw} = 1.2\ (64\ \text{lb/ft}^3)$

$\rho_r = 76.8\ \text{lb/ft}^3$

$\frac{\pi}{4} OD^2 = \frac{M}{\rho r}$ * OrcaFlex equation for Outer Diameter

$OD = \sqrt{\left(\frac{4}{\pi}\right)\frac{M}{\rho_r}} = \sqrt{\left(\frac{4}{\pi}\right)\left(\frac{0.6\ \text{lbs/ft}}{76.8\ \text{lb/ft}^3}\right)}$

$\boxed{OD = 0.10\ \text{ft}}$

Spectra Calculations

$SG = 0.98 \quad \rho_{sw} = 64\ \text{lb/ft}^3 \quad M = 0.218\ \text{lb/ft}$

$\rho_r = 0.98\rho_{sw} = 0.98\ (64\ \text{lb/ft}^3)$

$\rho_r = 62.72\ \text{lb/ft}^3$

$\frac{\pi}{4} OD^2 = \frac{M}{\rho r}$

$OD = \sqrt{\left(\frac{4}{\pi}\right)\left(\frac{M}{\rho r}\right)} = \sqrt{\left(\frac{4}{\pi}\right)\left(\frac{0.218\ \text{lb/ft}}{62.72\ \text{lb/ft}^3}\right)}$

$\boxed{OD = 0.067\ \text{ft}}$

B. TRIAXYS Buoy Specifications (AXYS 2010)

Item		Specification	
Physical Description			
Diameter:			
Nominal Outside Diameter around bumper		1.10 m (43.5 inches)	
Diameter of SS hull		0.91 m (36 inches)	
Weight (including four batteries)		197 kg (435 lb)	
Weight (excluding batteries)		90 kg (199 lb)	
Obstruction Light		Amber LED source. Programmable. Three miles visibility	
Purge Port		¾" 16 UNF torqued to 20 N-m (14.5 ft-lbs)	
Dome Clamp SS316 M8 nuts torque		18 to 22 N-m (13-16 ft-lbs).	
Materials			
Hull		Stainless steel	
Dome		Polycarbonate Lexan Se (tested to ASTM D3763 and ISO 6603-2 impact specifications)	
Solar Panel Assembly		Fibreglass over foam	
Clamping ring		Stainless steel	
Sensors/Processor			
Water temperature		Thermilinear composite network	
Accelerometers		Flexure suspension servo (Range ±2g)	
Rate		Piezoelectric gyroscope (Maximum angular velocity ±100°/s)	
Compass		Microprocessor controlled fluxgate (Accuracy ± 0.5°)	
A/D and sampling frequency		8 channel 14 bit at 4 Hz	
Microprocessor		TMZ104 and WatchMan500	
GPS		12 channel in Skywave Inmarsat DMR200 Transceiver	
Resolution/Accuracy			
	Range	Resolution	Accuracy
Heave	±20 m	0.01 m	Better than 2%
Period	1.56 to 30 seconds		
Direction	0 to 360°		±1°
Water Temperature	-5 to +50°C		±0.1°C
Power System			
Operational system voltage		11.0 to 14.1 VDC	
Batteries		4 @ GNB SunLyte 5000X 12 volt,100 amp hr	
Solar Panels		10 @ 6 watt Siemens SM6	
Smart Charger		Sunsaver-6	
On/off Switch		**Turns buoy on when Magnetic Key is removed**	
Telemetry			
30 to 50 MHz or IRIDIUM Satellite or GSM, GPRS or CDMA		Synthesized VHF transmitter, FSK SIMPLEX Modem Short Burst Data Cellular Telephone Network	
Data Format		Binary or Hexadecimal transmission	
Transmission Rate		1200 to 9600 Baud depending on Radio-Modem	
Maximum Range (VHF Line of sight)		16 km (10 miles) typical over water (less over land)	
Optional secondary transmission		ARGOS or INMARSAT D+	
Optional Watch-Circle Beacon		ARGOS or INMARSAT D+	

C. AWAC Specifications (Nortek 2013)

System	
Acoustic frequency:	1MHz, 600kHz or 400kHz
Acoustic beams:	4 beams, one vertical, three slanted at 25°
Vertical beam opening angle:	1.7°
Operational modes:	Stand-alone or online monitoring

Current Profile	
Maximum range:	30m (1MHz), 50m (600 kHz), 100m (400kHz) (depends on local conditions)
Depth cell size:	0.25 – 4.0m (1MHz) 0.5 – 8.0m (600kHz) 1.0 – 8.0m (400kHz)
Number of cells:	Typical 20–40, max. 128
Maximum output rate:	1Hz

Velocity measurements	
Velocity range:	±10 m/s horizontal, ±5 m/s along beam
Accuracy:	1% of measured value ±0.5 cm/s

Doppler uncertainty	
Current profile:	1cm/s (typical)

Wave measurements	
Maximum depth:	35m (1MHz), 60m (600 kHz), 100m (400kHz)
Data types:	Pressure, one velocity along each beam, AST*
Sampling rate (output):	2 Hz velocity, 4 Hz AST* (1MHz), 1 Hz velocity, 2Hz AST* (600kHz), 0.75 Hz velocity, 1.5Hz AST* (400kHz)
No. of samples per burst:	512, 1024, or 2048. Inquire for options

Wave estimates	
Range:	-15 to +15m
Accuracy/resolution (Hs):	<1% of measured value/1cm
Accuracy/resolution (Dir):	2° / 0.1°
Period range:	0.5-100s (1MHz), 1 - 100s (0.6MHz), 1.5 - 100s (0.4MHz)

Depth(m)	cut-off period (Hs)	cut-off period (dir)
5	0.5 sec	1.5 sec
20	0.9 sec	3.1 sec
60	1.5 sec	4.2 sec
100	2 sec	5.0 sec

Sensors	
Temperature:	Thermistor embedded in housing
Range:	–4°C to 40°C
Accuracy/ Resolution:	0.1°C/0.01°C
Time constant:	<5 min
Compass	Magnetoresistive
Accuracy/Resolution:	2°/0.1° for tilt <15°
Tilt:	Liquid level
Maximum tilt:	30°, AST* requires <10° instrument tilt
Up or down:	Automatic detect
Pressure:	Piezoresistive
Standard range:	0–50 m (1MHz) / 0-100m (0.6MHz) / 0-100m (0,4MHz)
Accuracy:	0.5% of full scale. Optional 0.1% of full scale.
Resolution:	0.005% of full scale

Transducer configurations	
Standard:	3 beams 120° apart, one vertical
Platform mount:	3 beams 90° apart, one at 5°

Materials	
Standard:	Delrin and polyurethane plastics with titanium screws

Connectors:	
Bulkhead (Impulse):	MCBH-2-FS
Cable:	PMCIL-8-MP

Environmental	
Operating temperature:	–4°C to 40°C
Storage temperature:	–20°C to 60°C
Shock and vibration:	IEC 721–3–2
Depth rating:	300m

Dimensions:	
	See drawing on front page
Weight in air:	7.3 kg (0.4MHz), 6.2 kg (0.6MHz), 6.1 kg (1MHz)
Weight in water:	3.6 kg (0.4MHz), 2.9 kg (0.6MHz & 1MHz)

Analog Inputs	
Number of channels:	2
Supply voltage to analog output devices:	Three options selectable through firmware commands: • Battery voltage/500mA • +5V/250mA • +12V/100mA
Voltage Input:	0-5V
Resolution:	16 bit A/D

Data Recording	
Capacity(standard):	2 MB, can add: 32/176/352MB or 4GB
Profile record:	Ncellsx9 + 120
Wave record:	Nsamplesx24 + 1KB

Data Communication	
I/O:	RS 232 or RS 422
Communication baud rate:	300–115200
Recorder download baud rate:	600/1200 kBaud for both RS232 and RS422
User control:	Handled via «AWAC» software, or ActiveX® controls. «SeaState» for online systems.
ProLog:	Provides NMEA ASCII or Binary output formats for processed wave and current data.

Power	
DC input:	9-18 VDC
Peak current:	3A
Power consumption:	Transmit power: 1–30W, 3 adjustable levels
Sleep consumption:	0.3 mW (RS232) 5 mW (RS422)

Real time clock	
Accuracy:	± 1min/year
Backup in absence of power:	1 year

Offshore Cable

The Nortek offshore cable can, when properly deployed, withstand tough conditions in the coastal zone. In RS 422 configuration, cable communication can achieved distances up to 5 km.

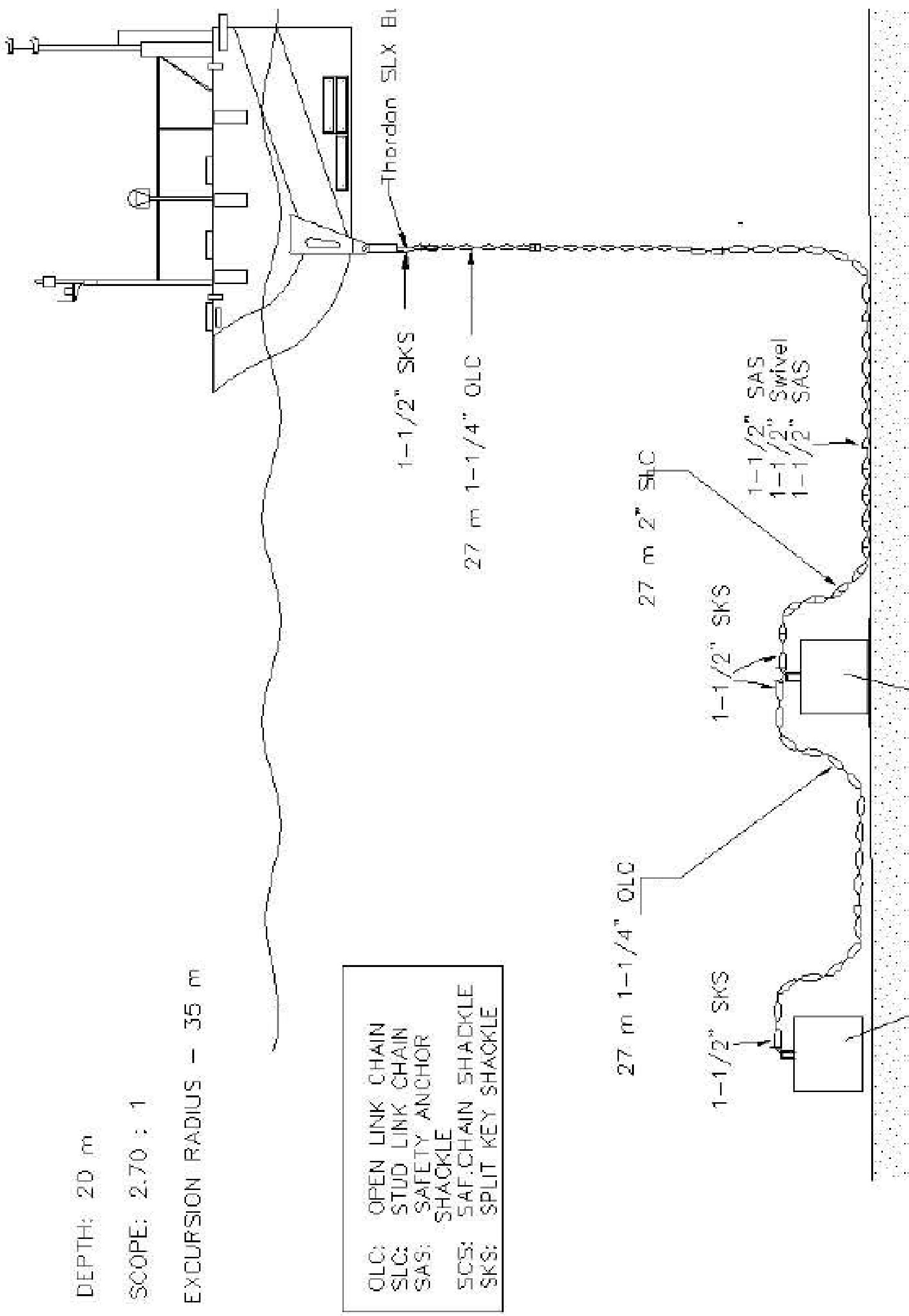
Online Projects

Nortek can provide long cables, radio/telephone communication equipment, acoustic modems, etc., that can meet the requirements of your specific project.

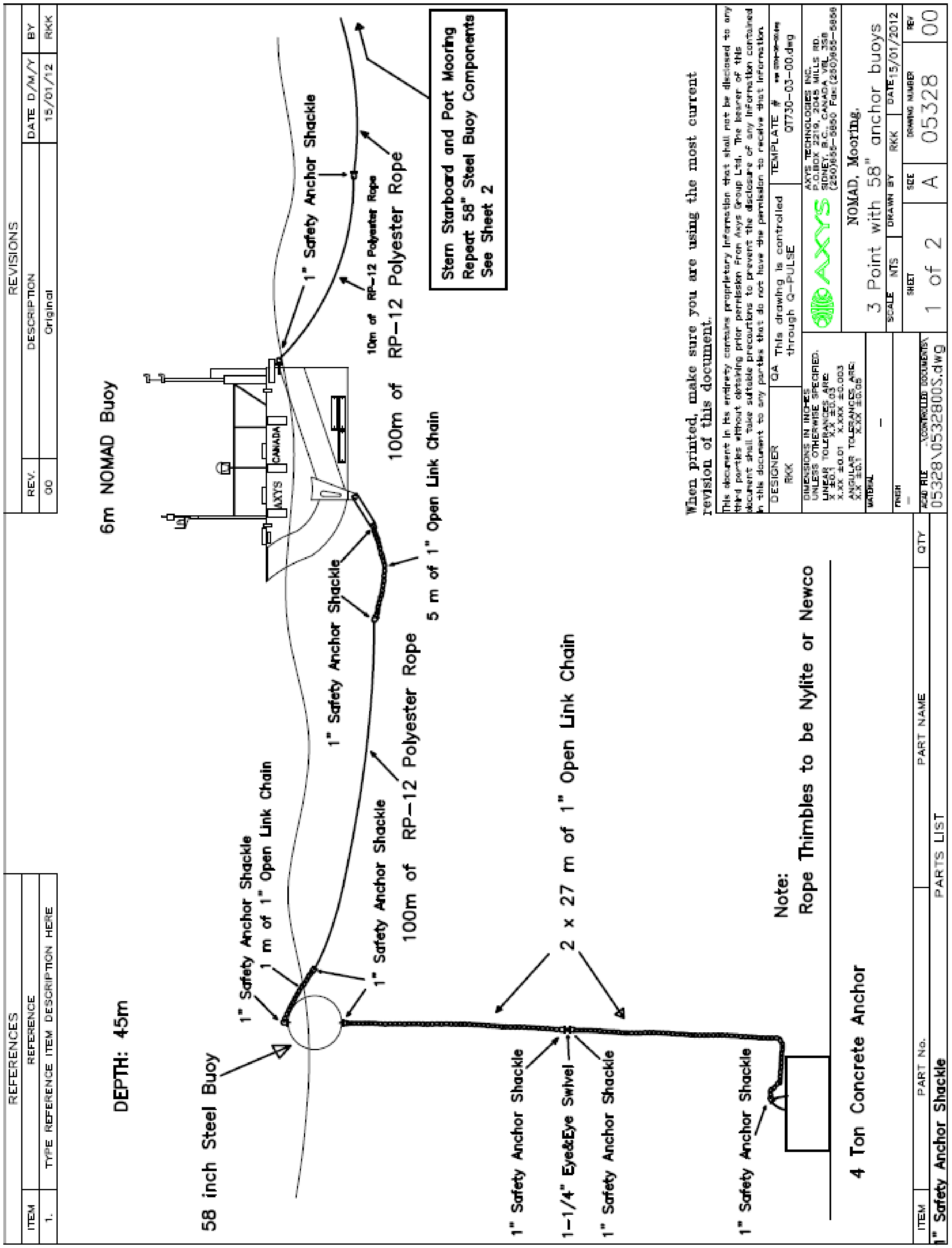
*) AST = Acoustic Surface Tracking

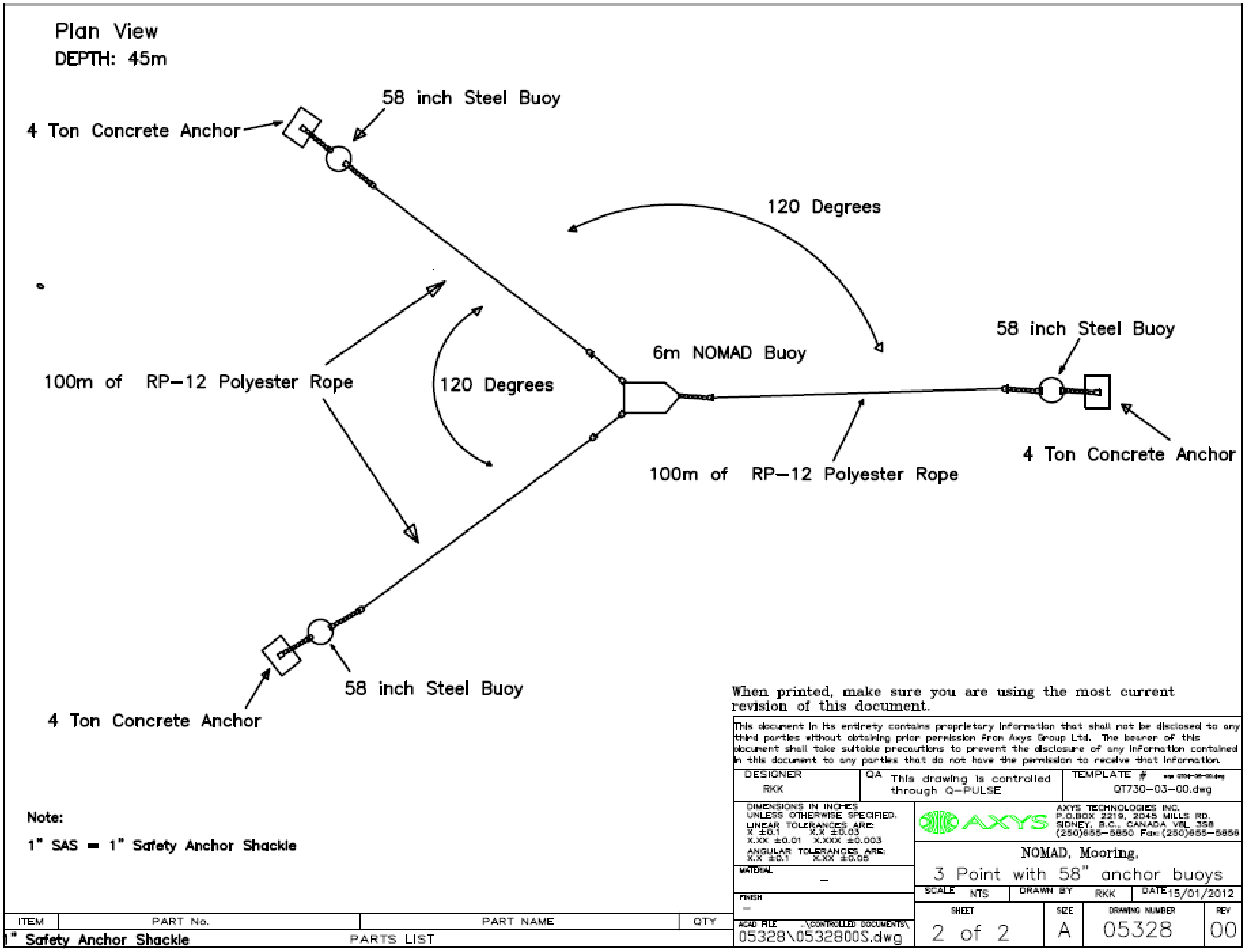
D. AXYS Technologies Mooring Designs

D.1 Example Single Point Mooring for NOMAD Buoy (AXYS 2012-b)

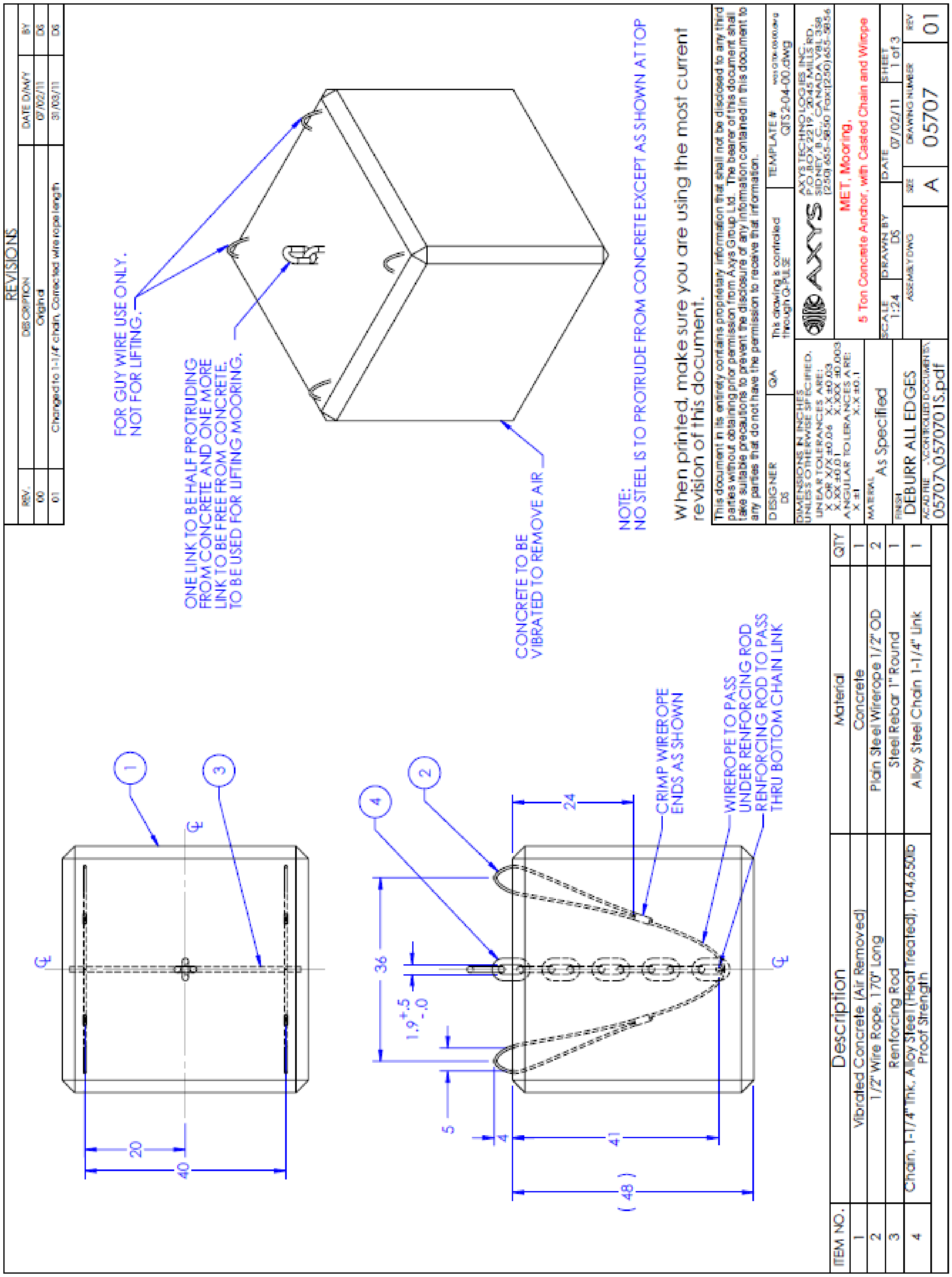


D.2 Ocean Sentinel Three-Point Mooring Design (AXYS 2012-a)

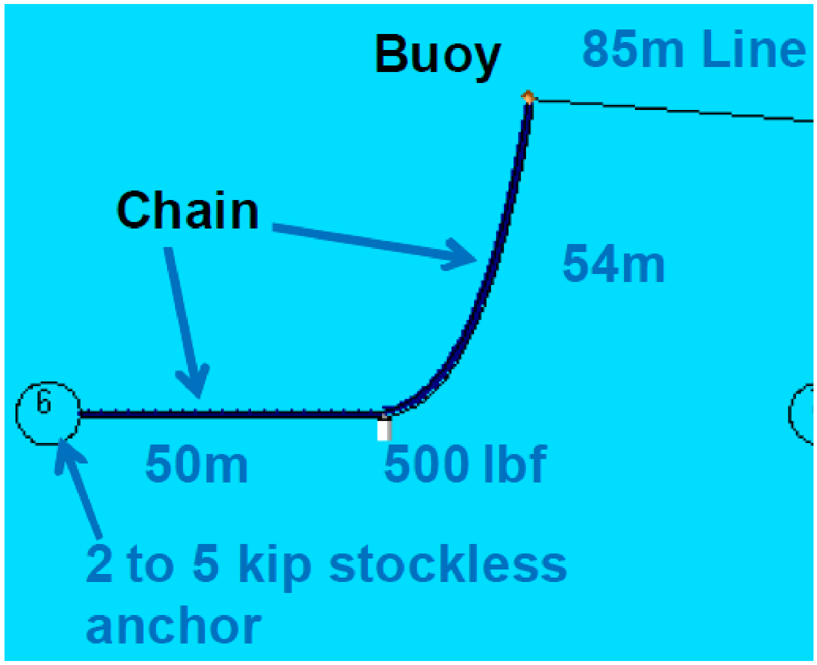


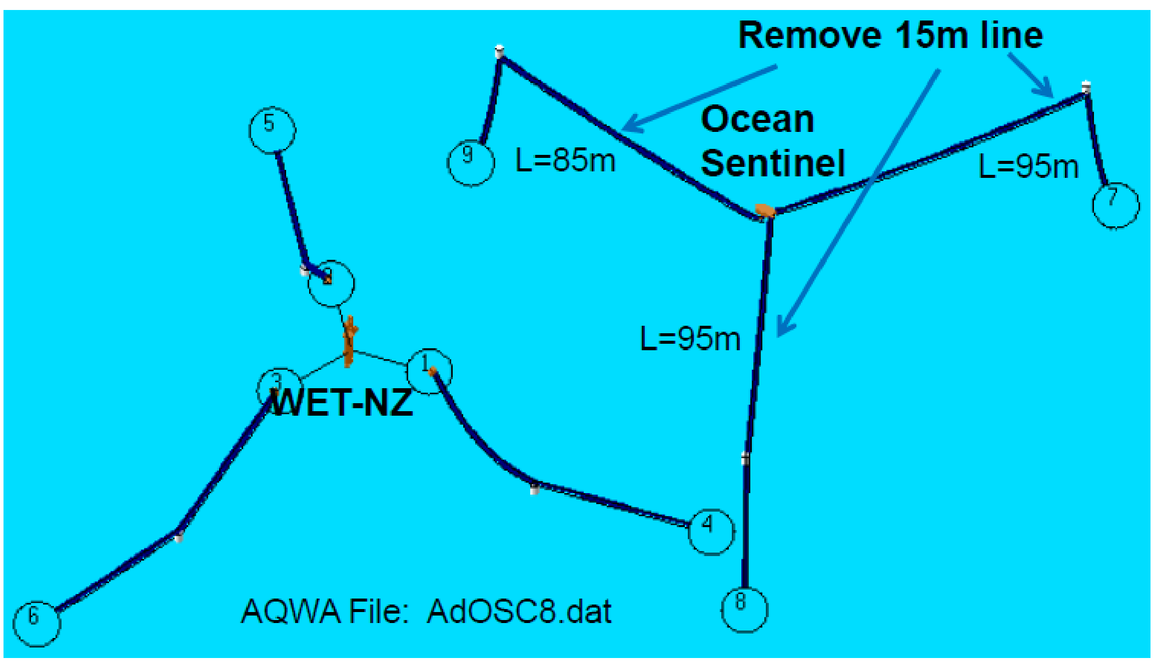

Plan View
DEPTH: 45m
4 Ton Concrete Anchor
58 inch Steel Buoy
120 Degrees
100m of RP–12 Polyester Rope
120 Degrees
6m NOMAD Buoy
58 inch Steel Buoy
100m of RP–12 Polyester Rope
4 Ton Concrete Anchor
58 inch Steel Buoy
4 Ton Concrete Anchor
Note:
1" SAS = 1" Safety Anchor Shackle
ITEM
PART No.
PART NAME
QTY
1" Safety Anchor Shackle
PARTS LIST
When printed, make sure you are using the most current revision of this document.
This document in its entirety contains proprietary information that shall not be disclosed to any third parties without obtaining prior permission from Axys Group Ltd. The bearer of this document shall take suitable precautions to prevent the disclosure of any information contained in this document to any parties that do not have the permission to receive that information.
DESIGNER RKK
QA This drawing is controlled through Q–PULSE
TEMPLATE #
QT730–03–00.dwg
DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED.
AXYS
AXYS TECHNOLOGIES INC.
NOMAD, Mooring,
3 Point with 58" anchor buoys
MATERIAL
FINISH
SCALE NTS
DRAWN BY RKK
DATE 15/01/2012
SHEET 2 of 2
SIZE A
DRAWING NUMBER 05328
REV 00
05328\05328005.dwg

D.3 Ocean Sentinel Anchor Specification (AXYS 2011)

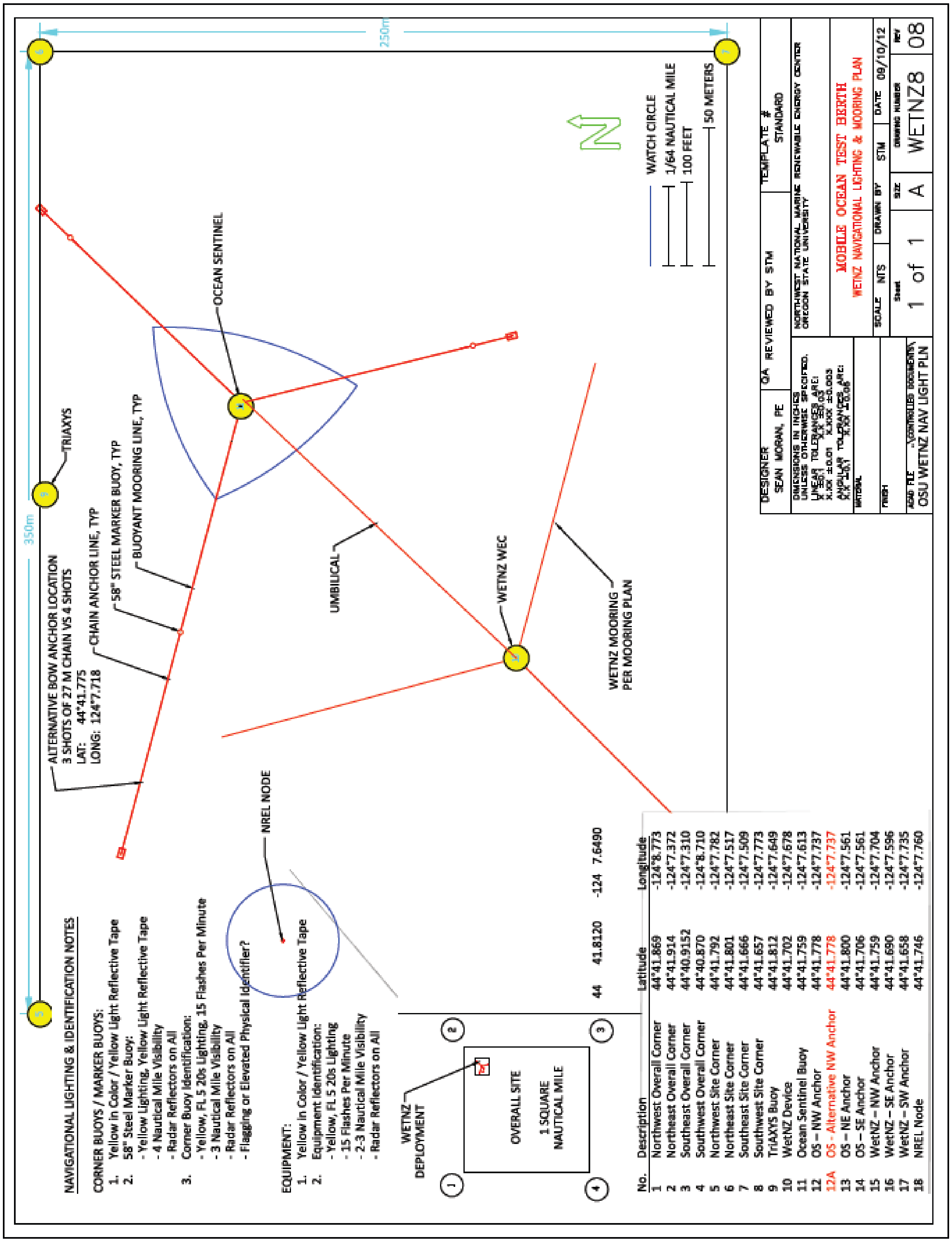


E. SST Ocean Sentinel Mooring Recommended Diagrams (SST 2012)





F. 2012 Ocean Sentinel Deployment Layout (Moran 2012)



No.	Description	Latitude	Longitude
1	Northwest Overall Corner	44°41.869	-124°8.773
2	Northeast Overall Corner	44°41.914	-124°7.372
3	Southeast Overall Corner	44°40.9152	-124°7.310
4	Southwest Overall Corner	44°40.870	-124°8.710
5	Northwest Site Corner	44°41.792	-124°7.782
6	Northeast Site Corner	44°41.801	-124°7.517
7	Southeast Site Corner	44°41.666	-124°7.509
8	Southwest Site Corner	44°41.657	-124°7.773
9	TriAXYS Buoy	44°41.812	-124°7.649
10	WetNZ Device	44°41.702	-124°7.678
11	Ocean Sentinel Buoy	44°41.759	-124°7.613
12	OS – NW Anchor	44°41.778	-124°7.737
12A	OS - Alternative NW Anchor	44°41.778	-124°7.737
13	OS – NE Anchor	44°41.800	-124°7.561
14	OS – SE Anchor	44°41.706	-124°7.561
15	WetNZ – NW Anchor	44°41.759	-124°7.704
16	WetNZ – SE Anchor	44°41.690	-124°7.596
17	WetNZ – SW Anchor	44°41.658	-124°7.735
18	NREL Node	44°41.746	-124°7.760

G. Load Cell Calibration Results (Amon & Lettenmaier 2013)

From factory calibration sheets: shunt resistor 75 kOhm (between negative excitation and negative signal):

- Bow 1 = 7457.4 lb
- Bow 2 = 7464.8 lb
- Port = 7414.9 lb
- Starboard = 7427.1 lb

From our shunt calibration: shunt resistor 74.4 kOhm (slightly lower resistance will result in higher load values measured):

- Bow 1 = not recorded
- Bow 2 = 7875 lb
- Port = 7780 lb
- Starboard = 7881 lb

Zero offset, before correction in LabVIEW (shunt resistor removed, load cell horizontal with no load):

- Bow1 = 228 lb
- Bow2 = 312 lb
- Port = 285 lb
- Starboard = 350 lb

Tension test on bow load cells (lifting yoke with chain hoist on load cells). From hoist down, components are: hoist, Dillon EDxtreme, Bow 1, Bow 2, yoke. Lower load cells measure less due to a decrease in hanging weight below them.

- Dillon EDxtreme: 830 lb
- Bow1 = 807 lb
- Bow2 = 778 lb

(roughly 25 lb per load cell weight)

Hanging RR wheel on Starboard side.

- RR wheel weight = approx. 625 lb, EDxtreme load cell agrees
- Pre-measurement w/ EDxtreme = 23 lb (load cell and shackles)
- Starboard load cell = 647lb
- Check: (647-23)/625 = 0.16%

H. National Marine Electronics Association (NMEA) 0183 Format

H.1 Sample Text File

$W5M5A,130729,000005,520c001e4525d1c4,1,4437.5265N,12402.6810W,1017.53,15.6,99.9,15.6,6.0,9.3,316,5.5,9.0,317,-75.2214,-0.624543,-0.407203,9.3,3.4,3.5,3.5,3.5*5B

$W5M5A,130729,000301,5204001e4525c325,1,1375054801,189,0.002,5.6,0.008,19.773,0.003,7.5,0.005,10.6,5.8,28.6,28.2,0.004,16.141,0.000,336,72,0,4437.8485N,12402.8676W,0,13.09,6142,1,25.8,1.35,3.6*44

$TSPAA,130729,000301,04231,TAS04231,4437.8485N,12402.8676W,1.65,25.8,970.90,1552.00,50,1.00,1314,138,1786,124,2154,137,2079,140,2198,131,2373,131,2229,138,2895,153,3262,159,3445,158,2260,145,2452,161,2185,154,1837,151,1855,142,1847,111,1631,132,1499,126,1436,125,1141,126,1138,133,1728,165,1410,137,1297,159,1091,146,516,135,877,128,1194,140,1419,150,974,130,1158,112,853,138,1188,120,1401,157,938,144,442,132,1127,102,861,136,827,117,556,106,1020,119,685,125,462,103,470,117,1290,135,1105,122,1072,112,864,98,669,100,1234,115*24

$TSPMA,20130728,234001,04231,TAB02282,4437.8455N,12402.8696W,76,0.030,0.005,335.99,72.07,1.849E-05,331.4,70.8,4.479E-05,1.5,71.6,2.855E-05,24.3,69.6,8.821E-06,16.6,71.0,7.184E-06,294.2,72.7,8.145E-06,251.0,72.7,7.042E-06,220.1,74.8,4.061E-06,194.3,78.5,2.284E-06,359.2,77.6,1.246E-06,21.8,75.6,8.298E-07,35.0,73.3,8.731E-07,37.8,70.9,9.411E-07,28.5,71.5,6.901E-07,1.1,76.0,5.829E-07,301.4,79.6,3.395E-07,108.5,79.9,2.894E-07,111.1,78.0,3.736E-07,289.6,77.8,3.394E-07,312.3,69.1,4.885E-07,312.8,61.6,4.871E-07,307.1,60.4,3.668E-07,290.7,66.3,3.452E-07,254.9,73.6,2.965E-07,223.6,75.5,2.663E-07,238.1,73.6,3.887E-07,250.1,71.6,4.336E-07,270.0,68.6,3.544E-07,288.3,67.5,2.682E-07,290.8,70.5,1.564E-07,282.3,77.0,1.083E-07,326.0,79.7,8.293E-08,348.0,76.8,5.508E-08,317.8,74.9,2.063E-06,297.8,67.0,6.560E-06,299.0,68.6,5.453E-06,295.6,70.7,2.354E-06,283.4,74.4,2.061E-06,265.9,76.6,1.971E-06,311.0,77.7,3.365E-06,306.4,74.5,3.502E-06,288.0,70.7,2.892E-06,264.4,69.8,2.915E-06,229.3,69.9,3.419E-06,206.0,68.8,3.741E-06,218.3,71.6,2.670E-06,266.2,75.1,2.277E-06,315.5,74.0,3.320E-06,332.4,74.1,3.767E-06,339.7,77.1,3.879E-06,105.3,78.6,2.953E-06,122.4,70.8,1.898E-06,118.5,66.2,2.030E-06,115.3,67.2,1.975E-06,104.6,75.0,2.022E-06,13.5,78.1,1.743E-06,40.2,76.2,1.203E-06,77.1,76.0,1.014E-06,290.9,77.6,7.955E-07,278.6,69.8,4.632E-07,273.8,72.6,5.710E-07,293.2,73.8,6.241E-07,315.1,72.3,8.714E-07,329.1,73.4,6.184E-07,341.9,72.9,3.527E-07,331.8,73.8,3.283E-07,296.6,79.5,5.296E-07,294.1,79.3,9.943E-07,312.9,76.2,8.344E-07,315.8,75.9,3.490E-07,312.5,77.1,1.733E-07,277.2,76.3,1.047E-07,279.6,70.2,1.167E-07,295.2,69.8,1.718E-07,301.5,70.7,1.852E-07,258.3,77.9,1.929E-07,156.6,72.6*03

H.2 NMEA Message Definitions (AXYS 2012-d)

H.2.1 NOMAD Message 1 – Met Message Definition

Field #	Field Name	Device Handler(s)	Units
N/A	*NMEA begin character*	*N/A*	*$*
N/A	*NMEA header*	*N/A*	*W5M5A*
N/A	*Transmission Date*	*N/A*	*XXXXXX*
N/A	*Transmission Time*	*N/A*	*XXXXXX*
N/A	*W500 Serial Number*	*N/A*	*520c001e4525d1c4*
N/A	*Message ID*	*N/A*	*1*
1	Current Position Latitude	GPS Generic	<degrees><decimal minutes><hemisphere>
2	Current Position Longitude	GPS Generic	<degrees><decimal minutes><hemisphere>
3	Average Pressure (mb)	Baro PTB100	mb
4	Average Air Temperature (C)	Rotronics ATH	°C
5	Average Humidity (%)	Rotronics ATH	%
6	Average Dew Point (C)	Rotronics ATH	°C
7	Average wind speed 1	Wind Generic - Vector	m/s
8	Last sampling interval gust speed 1	Wind Generic - Vector	m/s
9	Average wind direction 1	Wind Generic - Vector	
10	Average wind speed 2	Wind Generic - Gill	m/s
11	Last sampling interval gust speed 2	Wind Generic - Gill	m/s
12	Average wind direction 2	Wind Generic - Gill	degrees
13	Yaw (deg)	ORIENTATION_MicroStrain	degrees
14	Pitch (deg)	ORIENTATION_MicroStrain	degrees
15	Roll (deg)	ORIENTATION_MicroStrain	degrees
16	SST	TEMP_YSI	°C
17	Flood sensor voltage	FLOOD_AXYS	V
18	Flood sensor voltage	FLOOD_AXYS	V
19	Flood sensor voltage	FLOOD_AXYS	V
20	Flood sensor voltage	FLOOD_AXYS	V
N/A	*End of NMEA Character*	*N/A*	***
N/A	*NMEA Checksum*	*N/A*	*XX*

H.2.2 TRIAXYS Message 1 – Data Definition

Field #	Field Name	Device Handler(s)	Units
N/A	*NMEA begin character*	*N/A*	*$*
N/A	*NMEA header*	*N/A*	*W5M5A*
N/A	*Transmission Date*	*N/A*	*XXXXXX*
N/A	*Transmission Time*	*N/A*	*XXXXXX*
N/A	*W500 Serial Number*	*N/A*	*5204001e4525c325*
N/A	*Message ID*	*N/A*	*1*
1	TAS Sampling Start Timestamp	TRIAXYS NW	s
2	Number of zero crossings	TRIAXYS NW	-
3	Havg – Average Wave Height	TRIAXYS NW	m
4	Tz – Mean spectral period	TRIAXYS NW	s
5	Hmax - Maximum Wave Height (m)	TRIAXYS NW	m
6	Tmax – Maximum Wave Period	TRIAXYS NW	s
7	Hsig - Significant Wave Height (m)	TRIAXYS NW	m
8	Tsig - Significant Period (seconds)	TRIAXYS NW	s
9	H10 – Highest 10^{th} of Waves	TRIAXYS NW	m
10	T10 – Average Period of Highest 10^{th} of Waves	TRIAXYS NW	s
11	Tavg – Average Period	TRIAXYS NW	s
12	Tp - Peak Period	TRIAXYS NW	s
13	Tp5 – Peak Period (Read Method)	TRIAXYS NW	s
14	HM0 – Significant Wave Height Spectral Moment	TRIAXYS NW	m
15	Te – Energy Period	TRIAXYS NW	s
16	Wave Steepness	TRIAXYS NW	-
17	Mean Wave Direction	TRIAXYS NW	degrees
18	Mean Spread	TRIAXYS NW	degrees
19	Wave Processing Return Value	TRIAXYS NW	0 = Pass
20	Current Position Latitude	GPS Generic	
21	Current Position Longitude	GPS Generic	
22	Watchcircle Position Status	GPS Generic	1-on position 0-offposition
23	System Voltage	Node Manager	V
24	Number of Resets	Node Manager	-
25	Log Error Count	Node Manager	-
26	SST	YSI Temperature	C
27	Mean Solar Current	Math Utility	A
28	Flood Current Input	ADC Input	V
N/A	*End of NMEA Character*	*N/A*	***
N/A	*NMEA Checksum*	*N/A*	*XX*

H.2.3 TRIAXYS Message 2 – WaveView ADCP Definition

Field #	Field Name	Device Handler(s)	Units
N/A	*NMEA begin character*	*N/A*	*$*
N/A	*NMEA header*	*N/A*	*TSPAA*
N/A	*Transmission Date*	*N/A*	*XXXXXX*
N/A	*Transmission Time*	*N/A*	*XXXXXX*
1	ID		XXXX
2	System ID		XXXXXXX
3	Latitude		<degrees><decimal minutes><hemisphere>
4	Longitude		<degrees><decimal minutes><hemisphere>
5	Depth		m
6	SST		C
7	Pressure		hPa
8	Soundspeed		cm/s
9	Number of Bins		
10	Bin size		m
11	ADCP Resultant String		Bin1 Magnitude, Bin 1 Direction, Bin 2 Magnitude, Bin 2 Direction,….., Bin “n” magnitude, Bin “n” Direction A comma delimited string representing the magnitudes and direction of the current of the different bins. Starting with bin 1 magnitude and the next field is bin 1 direction followed by bin 2 magnitude and so on.
N/A	*End of NMEA Character*	*N/A*	*
N/A	*NMEA Checksum*	*N/A*	*XX*

H.2.4 TRIAXYS Message 3 – MeanDir Definition

Field #	Field Name	Device Handler(s)	Units
N/A	*NMEA begin character*	*N/A*	*$*
N/A	*NMEA header*	*N/A*	*TSPMA*
N/A	*Start of Sample Date*	*N/A*	*XXXXXX*
N/A	*Start of Sample Time*	*N/A*	*XXXXXX*
1	Serial ID		XXXX
2	BuoyID		XXXXXXX
3	Latitude	GPS Generic	<degrees><decimal minutes><hemisphere>
4	Longitude	GPS Generic	<degrees><decimal minutes><hemisphere>
5	Number of Bands	TRIAXYS NW	(This may vary from one sample interval to the next) If measurements are below a threshold they are not included
6	Initial Frequency	TRIAXYS NW	= 0.03Hz
7	Frequency Spacing	TRIAXYS NW	= 0.005Hz
8	Mean Avg Direction	TRIAXYS NW	deg
9	Spread Avg Direction	TRIAXYS NW	deg
10	Energy 1	TRIAXYS NW	m^2/Hz
11	Mean Direction 1	TRIAXYS NW	deg
12	Direction Spread 1	TRIAXYS NW	deg
13	Energy “2”	TRIAXYS NW	m^2/Hz
14	Mean Direction “2”	TRIAXYS NW	deg
15	Direction Spread “2”	TRIAXYS NW	deg
…	….	TRIAXYS NW	
…	….	TRIAXYS NW	
…	…..	TRIAXYS NW	
…	Energy “N”	TRIAXYS NW	m^2/Hz
…	Mean Direction “N”	TRIAXYS NW	deg
…	Direction Spread “N”	TRIAXYS NW	deg
N/A	*End of NMEA Character*	*N/A*	*
N/A	*NMEA Checksum*	*N/A*	*XX*

I. Data Errors

- OS_PW_data_20130729_0000.txt
    - 03:00:00
        - $TSPAA (Current data)
            - After “74” there was another message appended (deleted this info and added ten zeros)
    - 13:20:00
        - $TSPMA (Spectral data)
            - 5.327E-0859E-07 (fixed to 5.327E-07)
            - 2.6.9 (deleted)
            - 2.674E-0799E-08 (fixed to 2.674E-07)
            - 84 (# of frequency bands; fixed to 78)
        - $TSPAA (Current data)
            - After “115” there was another message appended (deleted this info and added twenty zeros)
- OS_PW_data_20130804_0000.txt
    - 15:59:59
        - $TSPMA (Spectral data)
            - The number of bins was not correct, and there was a spurious number in the data
            - Deleted “5.408” between “39.3” and “8.706E-02”
            - Changed # of bins from “110” to “108”
    - 20:19:59
        - $TSPAA (Current data)
            - No direction value between “288” and “260”. Inserted “170” for direction, because it was the average of the direction values before and after (174 and 168)
            - Added eight zeros on the end to make it the same length as the rest of the files
    - 20:39:59
        - $TSPMA (Spectral data)
            - The number of bins is not correct, and there is one extra data line
            - Deleted “312.02” between “3.339E-02” and “318.1”
            - Changed # of bins from “92” to “90”
- OS_PW_data_20130805.txt
    - 00:59:59

        - $TSPMA (Spectral data)
            - 1.700E-0.530E-2 (fixed to 1.700E-02)
            - Changed # of bins from "107" to "105"
    - 14:39:59
        - $TSPMA (Spectral data)
            - There was no energy or direction value for one of the bins Inserted "0.90" and "295" (average of closest values) between "42.4" and "46.7"
            - The last bin has incorrect direction and spread data (deleted).
            - Changed # of bins from "107" to "105"
    - 14:59:59
        - $W5M5A (Ocean Sentinel data)
            - Too many commas after "9.5", which is temperature (deleted 2 commas)
    - 15:59:59
        - $TSPMA (Spectral data)
            - Spurious data: "2.509" between "47.5" and "0.01913" (deleted)
            - The last bin is bad (deleted)
            - Changed bins from "94" to "91"
- OS_PW_data_20130821.txt
    - 09:30:59
        - $TSPMA (Spectral data)
            - 1.311E7.814E-02 (changed to 7.814E-02)
            - Changed # of bins from "86" to "84"
- OS_PW_data_20130908.txt
    - 21:20:00
        - $TSPAA (Current data)
            - The last two bins had the start of another message appended to them (repeated data from previous bins)

J. OrcaFlex Theory

OrcaFlex has been used by the offshore industry since 1986, so there is a lot of information available about the software from Orcina and third-parties. Only some of the OrcaFlex theory is explained in this section, which includes: model components, forces calculated by the software, analysis methods, and environmental inputs. OrcaFlex version 9.3 was used for this study, and the OrcaFlex Manual was used as the main source for this section of the report (Orcina 2012).

J.1 Components

OrcaFlex offers seven types of components for building a model: vessels, 3D buoys, 6D buoys, Lines, Links, Winches, and Shapes. These components can be edited, arranged, and connected in a variety of ways that may go beyond what is implied by each component name.

Vessels are rigid bodies used to model ships, barges, platforms, and other large floating objects. They have six Degrees of Freedom (DOF) and motion characteristics are defined by the user, either through a time history file or Response Amplitude Operators (RAOs). RAOs are not provided by OrcaFlex, and must be obtained from model tests or more specialized computer programs. Six RAOs (one for each DOF) are input for each wave period and direction, and the number of waves/directions is determined by the user. The user can input displacement or load RAOs, or both, as well as stiffness, damping, and added mass matrices for each wave/direction. Vessels can also be driven around the surface during a simulation.

3D buoys are rigid bodies with three DOF (translation only), whose motion is calculated by OrcaFlex. They are simple point bodies intended to model small objects where rotation is not important, such as floats or marker buoys.

6D buoys are rigid bodies with six DOF, whose motion can be specified through RAOs or directly calculated by OrcaFlex. There are three types of 6D buoys: lumped buoys, spar buoys, or towed fish. 6D buoys can be used to model any rigid body where full motion is desired, and do not have to be buoyant.

Lines are finite elements that can be used to model mooring lines, cables, umbilicals, hoses or pipes. They can have varying properties along their length, as well as multiple attachments. Line ends can be free, fixed, anchored to the seabed, or connected to other objects. Ends can also be disconnected at various points throughout a simulation.

Links are massless objects that can be used instead of lines to connect two objects in the model.

Winches are massless, and can be used to connect two or more objects in the model. Winches have a wire, which is used for the connections, and a drive, which controls the wire. Drives can operate during a simulation with constant speed or constant tension.

Shapes are massless objects that are available in two types (solid or trapped water) and four geometries (plane, block, cylinder, or curved plate). They consist of an elastic material, and will provide a reaction force if penetrated by another object. They can be fixed, anchored, or connected to another object. Shapes can used to model a variety of real-world objects, including ballast tanks, moon-pools, seawalls, or rocks.

J.2 Forces

There are eleven basic forces used and solved by OrcaFlex during an analysis: weight, buoyancy, drag, tension, shear, bending, torque, reaction forces, friction, contact forces, and forces applied by links and winches. Some of these forces do not require further explanation or do not apply to this study. However, more detail is provided on the methods and assumptions used by OrcaFlex for solving buoyancy, drag, tension, reaction forces, and friction.

J.2.1 Buoyancy

The default setting in OrcaFlex is to model buoyancy with no depth variation, so each object is considered incompressible. The buoyancy force is given by Equation 7.

$$B = \rho_{water} g V_{object} \tag{7}$$

Compressibility can be modeled for 3D buoys, 6D buoys, and Lines by specifying a Bulk Modulus for the object. However, this will only affect the buoyancy calculation; hydrodynamic drag from currents and waves is calculated using uncompressed volume and sea surface density.

J.2.2 Drag

There are three types of drag calculated by OrcaFlex: hydrodynamic, aerodynamic, and hydrodynamic with added mass effects. The Morison Equation (Equation 8) is used to calculate drag for 3D buoys, 6D buoys without RAOs, and lines. Both parts of the Morison Equation are used to calculate hydrodynamic drag with added mass (wave loads), while just the second part is used for aerodynamic and hydrodynamic drag with no inertia effect (wind and current loads). For Vessels, wave loads are calculated using RAOs, while current and wind loads are calculated using the Oil Companies International Marine Forum method (OCIMF 1994).

$$F_w = (\Delta \cdot a_w + \Delta \cdot C_a a_r) + \frac{1}{2}\rho C_d A V_r |V_r| \tag{8}$$

F_w = wave force
Δ = mass of fluid displaced by body
a_w = fluid acceleration relative to earth
C_a = added mass coefficient for body
a_r = fluid acceleration relative to body
ρ = fluid density
C_d = drag coefficient for body
A = drag area
V_r = fluid velocity

The first part of the Morison equation in parentheses is known as the inertia force, which is related to the fluid acceleration. The inertia force is made up of the Froude-Krylov component ($\Delta \cdot a_w$), and the Added Mass component ($\Delta \cdot C_a a_r$). The second part of the Morison equation is the drag force, which is related to fluid velocity.

J.2.3 Tension

Tension force only applies to Lines, and it is calculated at the center of each Line segment. There are two components to this force, effective tension and wall tension, which are given by Equations 9 and 10, respectively.

$$T_e = T_w + (P_o A_o - P_i A_i) \tag{9}$$

$$T_w = EA\varepsilon - 2v(P_o A_o - P_i A_i) + EAe \frac{\left(\frac{dL}{dt}\right)}{L_o} \tag{10}$$

E = Young's modulus
A = cross-sectional area
ε = total mean axial strain
L = instantaneous segment length
L_o = unstretched segment length
v = Poisson ratio
P_i , P_o = internal and external pressure
A_i , A_o = internal/external cross sectional stress area
e = damping coefficient of the line
$\frac{dL}{dt}$ = rate of increase of length

The internal pressure terms do not apply for cables, umbilicals, or ropes, and both the internal and external pressure terms do not apply for chains.

J.2.4 Reaction Forces

Both the seabed and solid shapes will provide a reaction force when objects come into contact with them. The reaction force is given by Equation 11, but for the seabed this only applies if "linear theory" is chosen (see Section J.4.1 for details on seabed theory).

$$F_R = KAd \tag{11}$$

K = stiffness of seabed or shape
d = depth of penetration
A = contact area

J.2.5 Friction

The friction force between solids or with the seabed is modeled as Coulomb friction (Equation 12); however a linear equation (Equation 13) is used for the critical area between positive and negative friction (see Figure 103), so that the force is solvable in this area.

$$f = \mu R \tag{12}$$

$$f = D_{crit} K_s A \tag{13}$$

μ = coefficient of friction
R = normal force
D_{crit} = critical deflection
K_s = shear stiffness
A = contact area

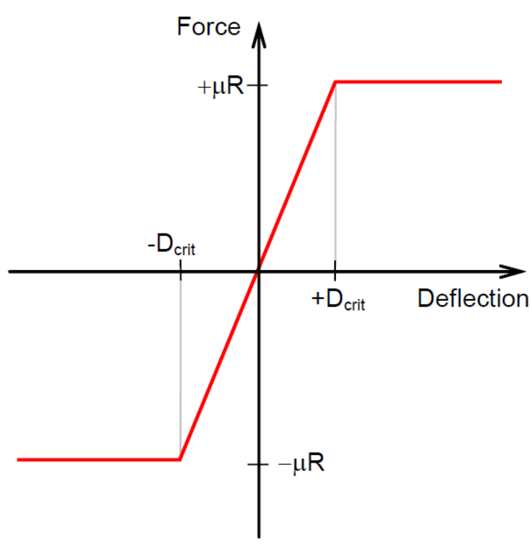


Figure 103: Modified Coulomb Friction Model (Orcina 2012)

J.3 Analysis Methods

There are three analysis methods offered by OrcaFlex: static, dynamic, and modal. A static analysis calculates all of the steady wind and current loads on the system, but does not include waves. A dynamic analysis is a time simulation that includes all static and variable loads on the system. A modal analysis calculates the undamped natural modes of the system, or modes of individual Lines. Static and dynamic analyses were used for all of the simulations in this study, and are explained below. The modal analysis feature was not used, but more information can be found in the OrcaFlex Manual (Orcina 2012).

J.3.1 Statics

The static analysis is used by OrcaFlex to determine the equilibrium position of the system before running a dynamic analysis. It takes into account all hydrostatic forces acting on a system, as well as constant wind and current forces, and is applied to all objects in the system.

The Line static analysis is the most complex, and has two steps. The first step is a fast analysis that will get close to the actual Line configuration, but may not always be the true equilibrium position. There are five options for step 1: Catenary, Spline, Quick, Prescribed, and User-Defined. Each option has its own assumptions and uses, but Catenary is recommended for most cases, and was used for all of the simulations in this study. The Catenary method ignores bending and torsional stiffness, as well as contact forces with solid shapes, but includes seabed touchdown and friction. It provides a position very close to equilibrium for regular catenary mooring lines, and is a good starting point for step 2. Step 2 is called Full Statics, and uses an iterative process to calculate all of the forces acting on a Line, and its true equilibrium position. Full Statics starts with the output from step 1, and generally takes much longer than step 1. Full Statics does not have to be used before starting a dynamic analysis; however, it provides more accurate initial conditions for the dynamic analysis.

Vessel and 3D/6D buoy statics are calculated using an iterative process, similar to Full Statics for Lines. These objects may be excluded from statics, and placed in a user-defined initial position at the start of a dynamic simulation. Longer computation times can result from including Vessels and 3D/6D buoys in the static analysis, but it provides more accurate initial conditions for the dynamic analysis.

J.3.2 Dynamics

The dynamic analysis is a time simulation that will predict the motions of the system for a specified time and environmental climate. It can be divided up into various stages where the environment or parts of the system change/move at each stage. For example, stages 1 and 2 may have different wave climates, and stage 3 may simulate the release of a buoy. The variety of combinations available can simulate complex operations in highly variable environmental conditions. For any dynamic analysis, there is always a build-up period, referred to as stage 0. The build-up slowly ramps-up the wave train and current to avoid shock loads to the system.

The dynamic analysis solves the equation of motion (Equation 14) for the entire system.

$$M(p,a) + C(p,v) + K(p) = F(p,v,t) \tag{14}$$

$M(p,a)$ = inertia load	p = position vector
$C(p,v)$ = damping load	v = velocity vector
$K(p)$ = stiffness load	a = acceleration vector
$F(p,v,t)$ = external load	t = time

This is done by computing the system geometry at each time step, which takes into account all geometric non-linearities and spatial variations of wave and contact loads.

There are two integration schemes available for the dynamic analysis, explicit and implicit, and static analysis results are used as input for both. The explicit scheme uses a direct integration method, but generally takes longer for a whole system analysis. The implicit scheme uses an iterative method to solve the equation of motion, and is generally faster for whole system analysis.

J.3.2.1 Explicit Integration Scheme

The explicit scheme uses a Forward Euler integration method with a constant time step. The equation of motion for each free-body and Line node is solved for the acceleration vector at the beginning of each time step, as shown in Equation 15. The velocity and position vectors at the beginning of the time step are then solved through integration. The acceleration vector at the end of each time step is solved using the Forward Euler scheme, as shown in Equation 16. The velocity and acceleration vectors at the end of the time step are solved in the same manner, and the process is repeated for every time step.

$$a_t = \frac{F(p,v,t) - C(p,v) - K(p)}{M(p)} \tag{15}$$

$$a_{(t+\Delta t)} = a_t + \Delta t \cdot a_t' \tag{16}$$

The explicit scheme is more efficient and requires less computation per time step than the implicit scheme. However, it generally requires much shorter time steps, so the computation time for analyzing a whole system is usually longer.

J.3.2.2 Implicit Integration Scheme

The implicit integration scheme uses the Generalized-α method, which was developed by Chung and Hulbert, 1993. This method uses ten equations that produce a set of “one-step, three stage numerically dissipative time integration algorithms” (Chung & Hulbert 1993). The forces, damping, and mass are all solved in the same manner as the explicit scheme, but the equation of motion is solved at the end of each time step for the whole system, as opposed to each individual node and free-body. This requires an iterative solution, so the computation time is much longer for each time step than the explicit scheme; however, the implicit scheme can generally handle much longer time steps, so it is usually faster than the explicit scheme.

J.4 Environment

J.4.1 Seabed

The seabed can be defined in OrcaFlex as flat or sloping, using depth, direction, and slope angle. It can also be defined using a 2D or 3D profile.

Reaction forces at the seabed can be modeled using linear or non-linear soil theory; however, the non-linear model was still experimental in the version of OrcaFlex used in this study. Accurate reaction forces become important when using drag anchors, piles, or anything that significantly penetrates the seabed, which was not the case for this study.

J.4.2 Current

A surface current is defined in OrcaFlex by its speed and the direction in which it is progressing. This surface current is extrapolated to all water levels above the Mean Water Line (MWL). A current depth profile can be defined through interpolation or the power law method.

When using interpolation, the user can define currents at any number of depths, and OrcaFlex will use linear interpolation to define currents between the defined depths. The currents at each depth are defined by a speed factor and a rotation angle. The speed factor is a percentage of the defined surface current. For example, if the current at 30 ft is half of the surface current, the speed factor = 0.5 at 30 ft. The rotation angle is the difference (in degrees) between the current direction and the defined surface current direction.

For the power law method, the user defines a current speed at the surface and the seabed, and the software calculates decay with depth using a power law equation. The user can define the equation exponent and the current direction, but the direction must be the same for all depths.

J.4.3 Wind

Wind only affects three types of objects in OrcaFlex: Vessels, Lines, and 6D buoys. Wind is defined by speed and the direction in which it is progressing. Wind speed is defined at 32.8 ft (10 m) above MWL, which is the standard used by the OCIMF vessel wind load model. To use wind speed measured at a different elevation, the user must convert the measured wind speed to a height of 32.8 ft by using Equation 17.

$$V(32.8) = V(h)\left(\frac{32.8}{h}\right)^{\frac{1}{7}} \tag{17}$$

h = height above MWL of measured wind speed

Air density can be defined by the user, but it is constant everywhere. Air kinematic viscosity is constant everywhere and cannot be edited by the user. Vertical variation of the wind above the MWL can be modeled using a vertical variation factor.

There are three types of wind that can be chosen: constant, random, or a time history. For constant wind, the wind will blow at the defined speed and direction for the entire simulation. For random wind there are two spectra available: NPD (Norwegian Petroleum Directorate) and API (American Petroleum Institute). The user can define the number of components, the number of random phases, and the wind time origin. For a time history, the user must have a time history file to load into OrcaFlex.

J.4.4 Waves

OrcaFlex offers a number of wave simulation options, including: regular waves (linear and non-linear), random waves (spectra), or a user-input time history. A wave train is defined by wave height, period, and the direction in which it is progressing. Depending on the type of wave simulation, there are also additional input options. OrcaFlex can only simulate non-breaking waves, and will give a warning if the user-defined wave conditions result in a breaking wave. A breaking wave is defined using the Miche Criterion (Equation 18).

$$H_b = 0.88k^{-1}\tanh(0.89kd) \tag{18}$$

J.4.4.1 Regular Waves

For regular waves, OrcaFlex has four options: Airy, Dean Stream Function, Stokes 5th Order, and Cnoidal. Airy is the only linear wave option, and the rest are non-linear waves. Airy should only be used for small waves in very deep water, or as a rough first approximation of system behavior. The Dean Stream Function is the most robust wave calculation offered by the software, and is recommended for all wave climates. Stokes 5th Order is a common wave equation used in engineering, and is applicable for many wave climates seen by offshore structures. Cnoidal theory is best suited for long waves in shallow water. If Stokes 5th Order or Cnoidal is used for the wrong type of wave, the software can provide inaccurate results. OrcaFlex will provide warnings for obvious misuses based on Equation 19, but the warnings may not cover all errors. OrcaFlex provides the following recommendations for choosing between the non-linear wave theories.

$$U = \frac{HL^2}{d^3} \tag{19}$$

U = Ursell number	U << 40	Dean or Stoke's 5th
H = wave height	U ~ 40	Dean
L = wave length	U >> 40	Dean or Cnoidal
d = water depth		

The Dean Stream Function is based on the stream function theory of Rienecker and Fenton, also called the Fourier approximation wave theory (Rienecker & Fenton 1981).

$$\Psi(x,z) = B_o z + \sum B_j \left[\frac{sinh(jkz)}{cosh(jk)}\right] cos(jkx) \quad (20)$$

k = wave number
(must be solved)

z = elevation
z = 0 @ seabed
z = d @ surface

j = 1 to N
N = order of stream function
B = coefficient that must be solved
x = displacement
Ψ = stream function

Equation 20 is solved numerically, and provides the best fit to the governing wave equations. Dean Stream requires more computation than Stoke's 5th Order or Cnoidal; however, it will provide good results for any wave climate if it converges. Input parameters when using the Dean Stream option include wave height, period, and direction, as well as the stream function order number.

J.4.4.2 Random Waves

OrcaFlex offers six options for random wave spectra: JONSWAP, ISSC (also known as Bretschneider or modified Pierson-Moskowitz), Ochi-Hubble, Torsethaugen, Gaussian Swell, and user-defined. Each spectrum is defined by wave height, period, and direction, as well as specific parameters for the spectrum. A more detailed description of each spectrum, as well as a list of the original reference documents, can be found in the OrcaFlex Manual (Orcina 2012).

OrcaFlex generates a wave spectra using linear superposition, where the user defines the number of linear wave components. Wave component frequencies are chosen using the equal energy approach, where each component has the same amount of energy (see Figure 104).

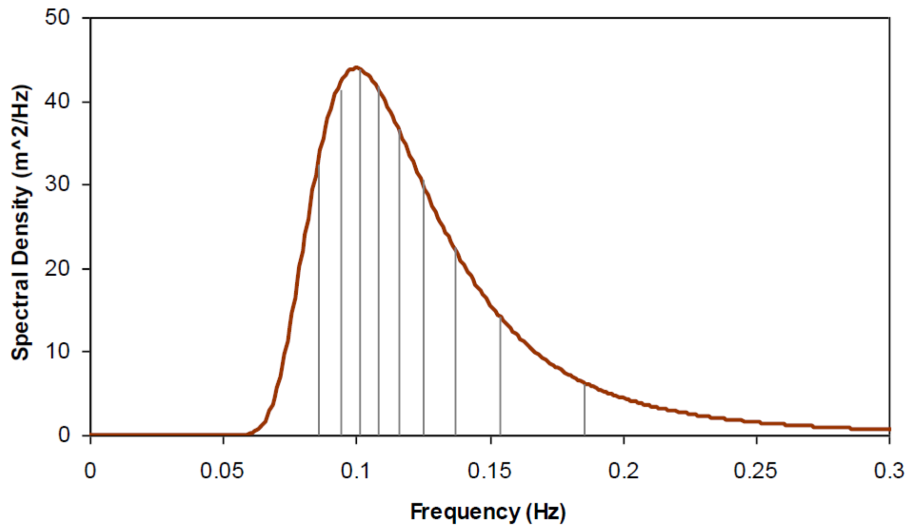


Figure 104: Wave component frequency divisions using equal energy (Orcina 2012)

OrcaFlex cites two main advantages to using the equal energy approach:

1. Wave component frequencies are not multiples of each other
2. There is finer discretization toward the peak.

However, as shown in Figure 104, the equal energy approach can result in wave components that span a large frequency range toward the tails of the spectrum, which can provide inaccurate model results. To address this, the user can define a maximum frequency span, whereby wave components will be further subdivided if they are larger than the max. Although this results in "unequal energy" toward the tails, it provides a more accurate representation of all of the frequencies.

The directional spread spectrum is defined by Equation 21, which is discretized into a user-defined number of wave directions, also using the equal energy approach:

$$S_d(\theta) = K(s)cos^{2s}\left(\theta - \theta_p\right) \qquad \text{for} \quad -\frac{\pi}{2} \leq \theta - \theta_p \leq \frac{\pi}{2} \qquad (21)$$

$K(s) = \pi^{-\frac{1}{2}}\frac{\Gamma(s+1)}{\Gamma\left(s+\frac{1}{2}\right)}$ - normalizing constant

$S(f,\theta) = S_f(f) \cdot S_d(\theta)$ - total spectrum

$2s$ - spreading exponent
θ - wave direction
θ_p - principal wave direction

Wave component phases are chosen using a random number generator. Although the phases are random, the sequence is repeatable, so the user will always see the same wave train with the same input conditions. Different phasing can be obtained by shifting the time origin of the simulation.